PART EIGHT

TECHNOLOGY TRANSFER SEMINARS ON MINE COMMUNICATIONS
AND THROUGH-THE-EARTH ELECTROMAGNETICS WORKSHOP

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# PART EIGHT

## TECHNOLOGY TRANSFER SEMINARS ON MINE COMMUNICATIONS AND THROUGH-THE-EARTH ELECTROMAGNETICS WORKSHOP

## I. TECHNOLOGY TRANSFER SEMINARS ON MINE COMMUNICATIONS

### A. INTRODUCTION

During the first quarter of 1973 ADL worked closely with PMSRC staff, under an extremely compressed time schedule, on all aspects of the detailed planning, organization and overall coordination and preparation of the lectures and in-mine demonstrations for the Bureau's Technology Transfer Seminar on Mine Communications given in March of 1973 to representatives of the mining industry.

Our efforts centered on the detailed organization and preparation of each of the five technical seminar lectures and associated supporting material, and the coordination of tasks assigned to ADL and other seminar participants. Revised and expanded drafts of the seminar papers were prepared from rough draft versions obtained from PMSRC, Collins Radio and ADL staff. Measurements were made to gather key data on the operation and performance of each of the following systems installed in the Bruceton Safety Research Mine; call alert paging, roof bolt paging, section wireless radio, and guided wireless radio systems. These data were analyzed, manufacturer's equipment specifications utilized, and calculations made to provide performance curves and data for each of the above systems.

A substantial amount of artwork was conceived and prepared for 35 mm slides, system identification posters in the mine, and seminar handouts. This artwork included some forty 8-1/2" x 11" line sketches, graphs, block diagrams, circuit diagrams, coverage maps, and other line drawings; five 30" x 40" block diagram system identification posters suitable for in-mine use; a 20" x 30" detail perspective illustration of a representative coal mine layout; forty viewgraphs; and seventy 35 mm slides of the artwork and word charts.

Conferences, discussions and review sessions were held with conference participants to help coordinate the various efforts, obtain technical information, and make final plans regarding the lecture presentations, associated visual aids, and the communication system installations to be demonstrated in the Bruceton mine. These meetings included final systems checkouts and dry run presentations and reviews of the lectures and mine demonstrations. This phase of the seminar effort concluded with R. Lagace and R. Spencer of ADL participating in two days of seminar presentations in the lecture hall and in the Bruceton mine.

This participation included the presentation of two papers coauthored with H. Parkinson of PMSRC, and entitled "Roving Miner, Paging" and "Two-Way Communications with Roving Miners."

The second phase of this seminar effort consisted primarily of preparing final edited versions of each of the five seminar papers, and typing them in a special draft format for subsequent processing and publication as an Information Circular* (IC) on Mine Communications by the Bureau's publication office. The specially formatted drafts of the two papers coauthored by ADL staff have been included in the following sections for convenient reference.

The final phase of the ADL seminar effort consisted in providing minor assistance to the Bureau in additional presentations of this seminar to the mining industry.

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* Information Circular No. 8635.

## B. ROVING MINER, PAGING

by

Richard H. Spencer[1] and Howard E. Parkinson[2]

ABSTRACT

Mine paging telephones increase the effectiveness of the mine personnel. The page message reaches the personnel within hearing distance of the phone. Personnel paging extends the page to the individual roving miner wherever he may be.

One system installed at the Bureau of Mines Safety Research mine is a "dial-in" system. An in-mine page can originate from any mine public phone. The system, exclusive of the Bell System equipment, includes an encoder, 88-kHz transmitter, pilot wire signal coupler, 88-kHz repeater, a roof bolt signal coupler, and pocket receivers.

There are two configurations of the system. One configuration is a whole mine configuration and the other is a working section configuration. There are two forms of the working section configuration. One form puts the selective page onto the mine phone line and converts the message to 88-kHz at the section, thereby extending the page area to the face.

The second form is a call alert system. This system keys a call alert transmitter on the section. The system has a capacity to handle 24 sections. It is a cost-effective system with an added feature of providing an emergency beacon locator at the time of a mine emergency.

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[2] Supervisory Electrical Research Engineer, Industrial Hazards and Communications, Pittsburgh Mining and Safety Research Center, Bureau of Mines, U.S. Department of the Interior, Pittsburgh, Pa.

## INTRODUCTION

### Current Paging Systems

Mine telephones are the backbone of most present mine communications systems. There are two main telephone instruments: the magneto telephone and the mine pager telephone. A large mine may have 40 or more of these phones. Selective calling is attempted on both types of phones. The magneto phone is used to make a selective call by a coded ring that is audible near each phone location. The mine pager phone is used to make a selective call by paging a particular individual by name over loudspeakers at the phone locations. The selective call feature of the mine pager phone is an improvement over that of the magneto phone, and as a result the mine pager phone has gained wide acceptance. These phones can be made permissible and because of their battery operation are ready for using during an emergency.

### Additional Paging Needs

The effectiveness of communication with roving miners underground would be significantly improved by meeting the following additional paging needs:

(1) Selective page to the desired individual

(2) Extention of paging coverage to individuals in all working places

Currently, there is confusion on the mine phone paging system. Individuals hear pages that are not meant for them, since it is a party line system. Individuals are frequently not within the acoustic range of a page phone loudspeaker, or may be in an area of high acoustic noise near machinery. Thus, many pages are not heard, and even if a page is heard, it is frequently hard to tell who is being paged, As a result, it is customary for many individuals to ignore pages unless a particular call is expected. This makes it difficult to get a reply to an incoming call, resulting in people often having to be dispatched into the mine to locate specific individuals. The root cause of this situation is that the mine pager phone message goes to the pager phones rather than to the specific individual being paged.

## PERSONAL PAGING VIA ROOF BOLTS

Personal paging extends the page message to the individual . A small pocket pager is carried by the individual. This pager receives a message only when the particular individual is being paged. The selective call feature of the page removes the confusion that is common in the mine page telephone system. Many personal paging systems are in use in a variety of communication applications. These systems are very effective in hospitals, industrial plants, and other large buildings. In their original form they are not satisfactory for mine use; however, relatively straightforward adaptations based on extensions of existing mine communication systems have proved to be fruitful. These adaptations are based on existing trolley wire and mine telephone systems, as described below.

Demonstration of paging capabilities was made by using carrier frequency equipment operating at the 88-kHz trolley wire phone frequency. Signals from the 88-kHz transmitter were connected to the leads of the main power system of the mine. The paging function was incorporated by using a commercial encoder manufactured by Reach to provide an input to the 88-kHz transmitter. This encoder provided 200 selective call numbers. Pocket pagers were given to several individuals to carry with them as they were roving underground. It was possible to reach them in most of the working places.

There were places, however, where the page signal was too weak thereby requiring the addition of equipment, namely an 88-kHz repeater. This repeater is fed by the 88-kHz signals on the power mains, and the output of the repeater is connected to roof bolts. This addition provided page capability up to the very face of the working sections.

The pocket pagers are selective and are operated only when the page messages are being transmitted. The normal trolley wire communications are not heard by an individual not being paged unless a button on the pager unit is depressed. We have continued to operate the equipment at 88-kHz; however, we recognize that it could be used at some other frequency that would preclude interference with normal 88-kHz transmissions.

## Principles of Operation

Figure 1 illustrates the current flow that results when two roof bolts are driven by a source of power. It is noted on this figure that

FIGURE 1. - Illustration of Current Flow Produced by Driving Roof Bolts.

the current flow extends far into the material surrounding the roof bolts. Indeed, at very great distances there is still current flow; the problem is that the currents are quite small compared to the background noise currents. One can easily see that if a pair of probes is attached to the material surrounding the roof bolts, even at great distances, voltages

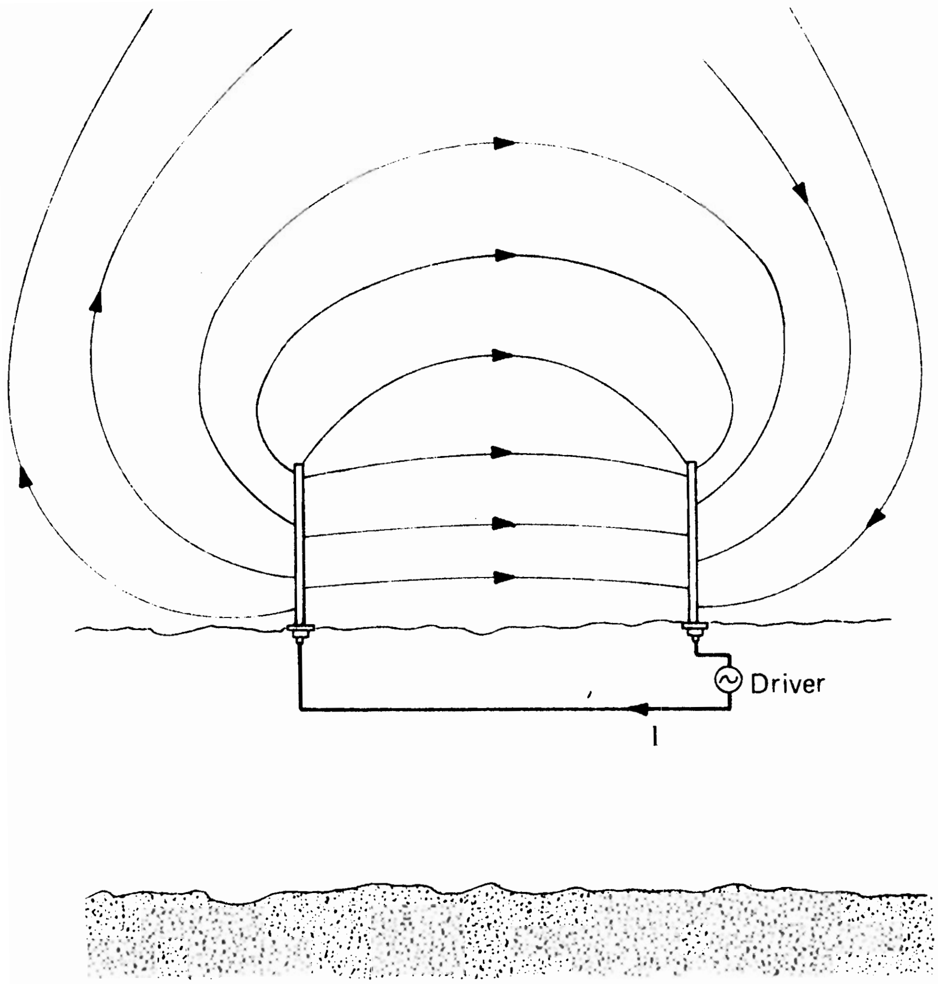


**FIGURE 1 ILLUSTRATION OF CURRENT FLOW PRODUCED BY DRIVING ROOF BOLTS**

produced by the current flow will be obtained from these probes. It is also evident that if the current flow is alternating, there will be associated magnetic fields which occur in the material and in the surrounding regions. These fields extend into the open areas of the mine and hence may be picked up by loop antennas throughout the mine region. It is important to know how far from the roof bolts one may obtain usable signals in this fashion.

## Expected Coverage

An experiment was conducted in the Bruceton Experimental mine as illustrated in Figure 2. An 88-kHz repeater of nominal 20-watt capability was attached to two roof bolts separated by a distance of approximately 120 feet. The repeater was driven from a sine-wave source, and a calibrated loop together with a calibrated receiver was used to measure the vertical magnetic field strength throughout all regions of the Bruceton mine. The manner in which roof bolt attachments were made is illustrated in Figure 3. A simple, direct electrical connection to roof bolts is illustrated here. The repeater is shown in Figure 4. Figure 5 shows the coverage to be expected with a Reach pocket pager receiver using the roof bolt system in the Bruceton mine. Three contours are shown on this

FIGURE 2. - Block Diagram of Roof Bolt Experiment.
FIGURE 3. - Roof Bolt Attachment.
FIGURE 4. - 88-kHz Repeater.
FIGURE 5. - Roof Bolt Coverage.

plot. The first contour is for a received signal-to-noise ratio of 15 db. This contour was determined by comparing the measured values of vertical

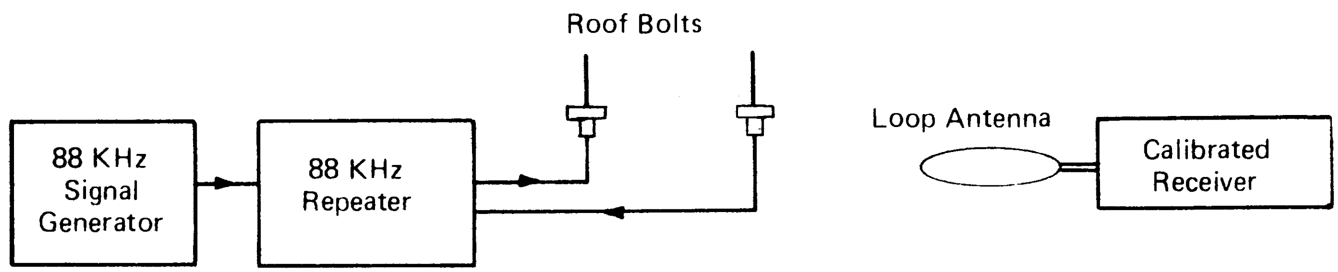


FIGURE 2 BLOCK DIAGRAM OF ROOF BOLT EXPERIMENT

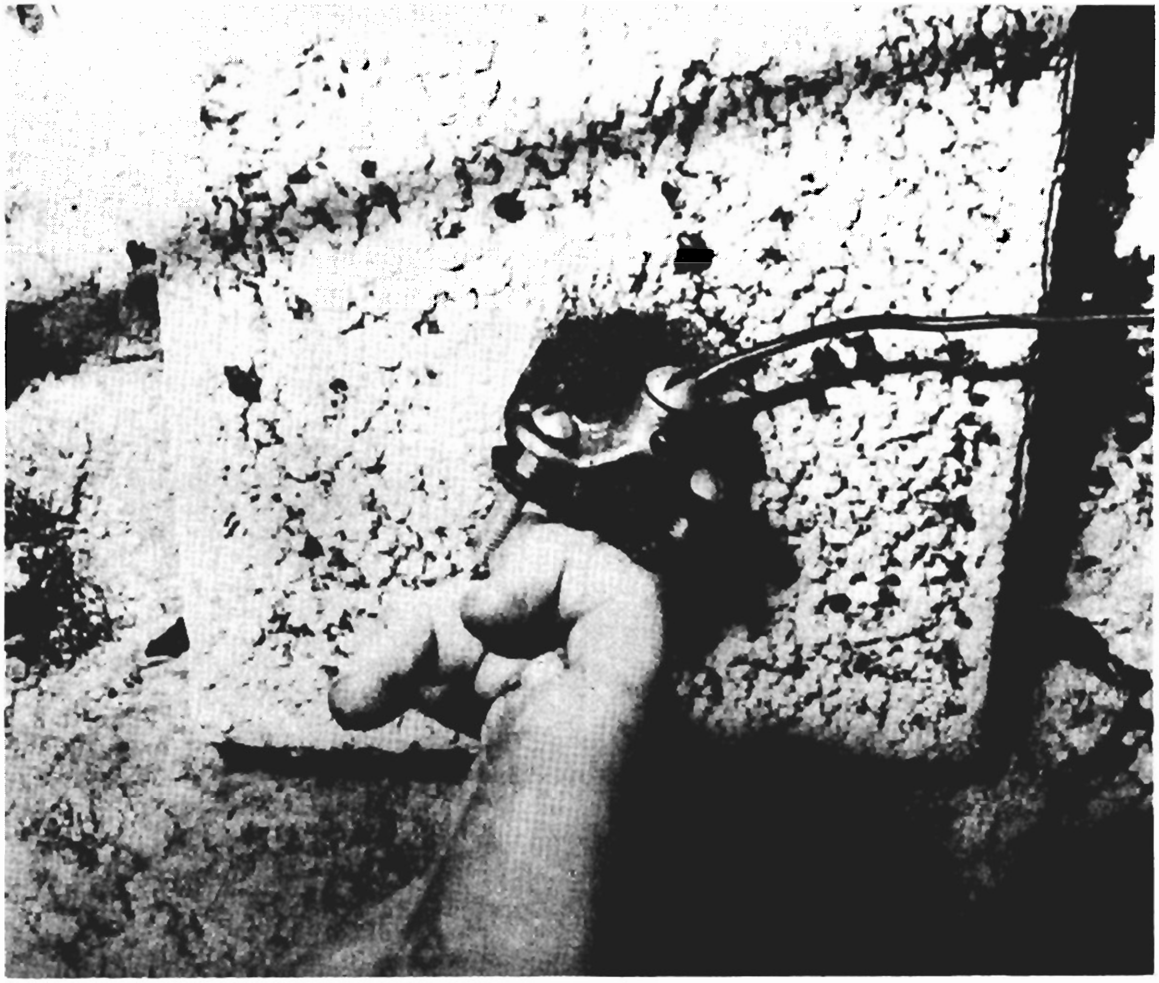

**FIGURE 3 ROOF BOLT ATTACHMENT**

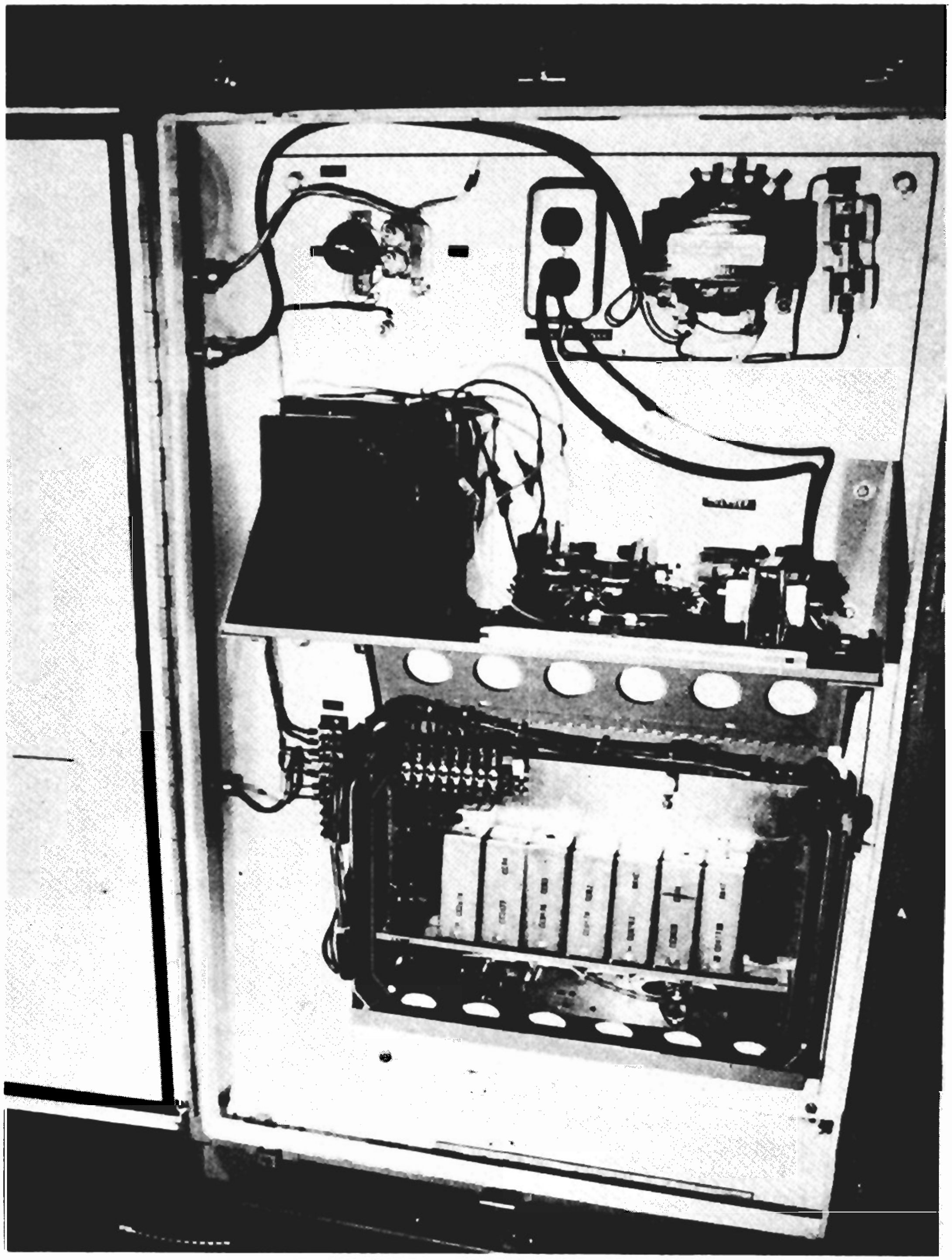

FIGURE 4 88 kHz REPEATER

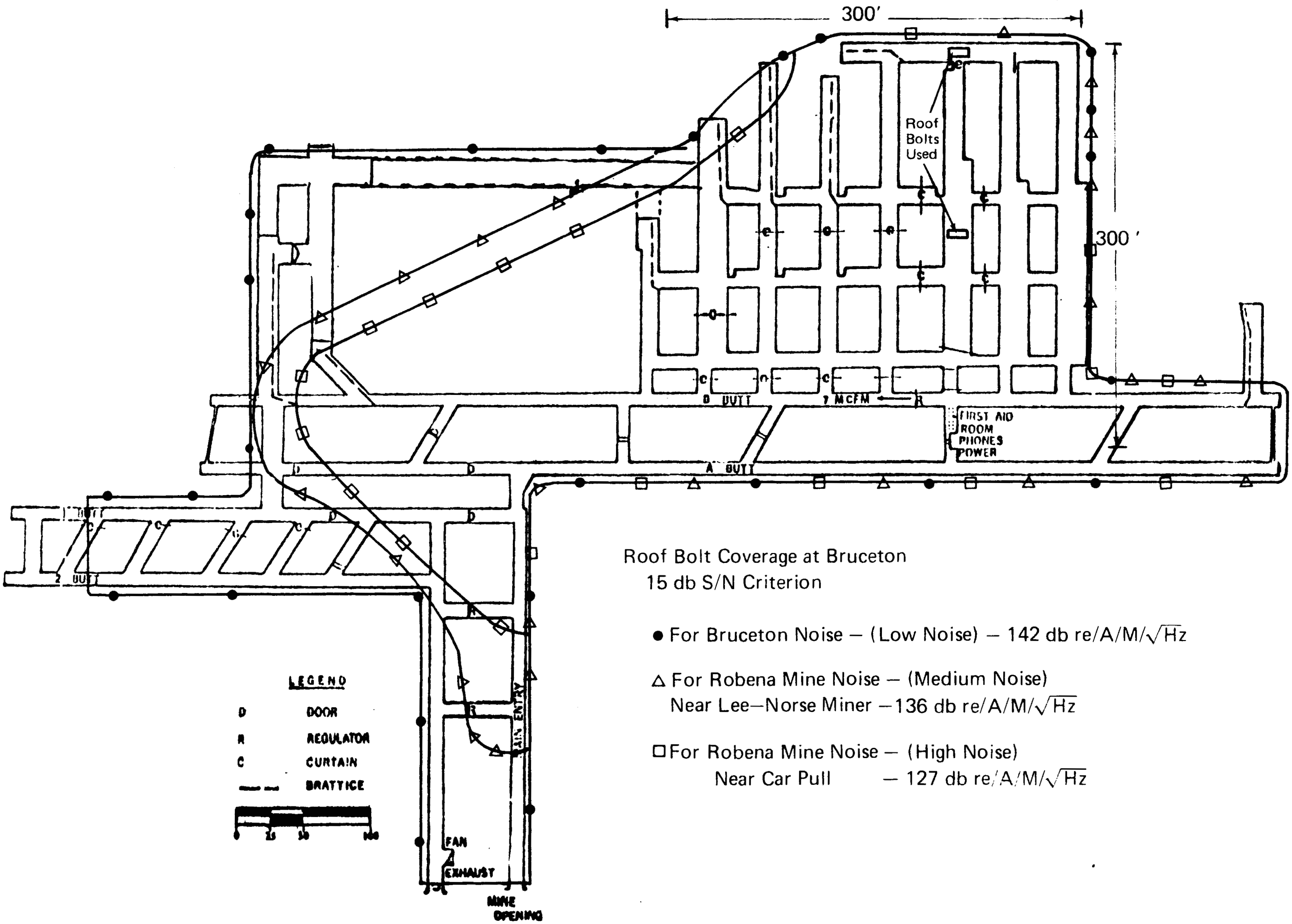


FIGURE 5 ROOF BOLT COVERAGE

magnetic field strength and the measured values of vertical magnetic field noise present during the experiment. A 2,000 Hz bandwidth was assumed for these determinations. It is seen that this boundary encloses essentially all of the Bruceton mine with the exception of a region at the far left extremity. Using the measured field strength data and noise obtained by the National Bureau of Standards (NBS) in their mine electromagnetic noise measurement program, two other contours are overlaid on this plot. The first one is the expected limit of coverage were the noise like that in the face area of a working mine near a Lee Norse miner. It is noted that this coverage is less than that for the Bruceton noise. The third contour represents the expected coverage were the noise like that found in the same working mine near a car pull while the car pull was operating. This machine produced the highest electromagnetic noise levels found by NBS in their mine measurements, and as such probably represent an upper limit of expected noise in mines at the frequencies of interest for mine communications. From these plots, it can be seen that coverage of a typical working section can be expected from roof bolt attachments made near the center of that section.

## System Description

The overall block diagram of the system as installed in Bruceton is shown in Figure 6. The paging system demonstrated in Bruceton can originate

FIGURE 6. - Whole Mine Paging System.

pages from any dial phone within the PBX at Bruceton. The caller dials 1, followed by a three-digit code. This connects his phone through the PBX

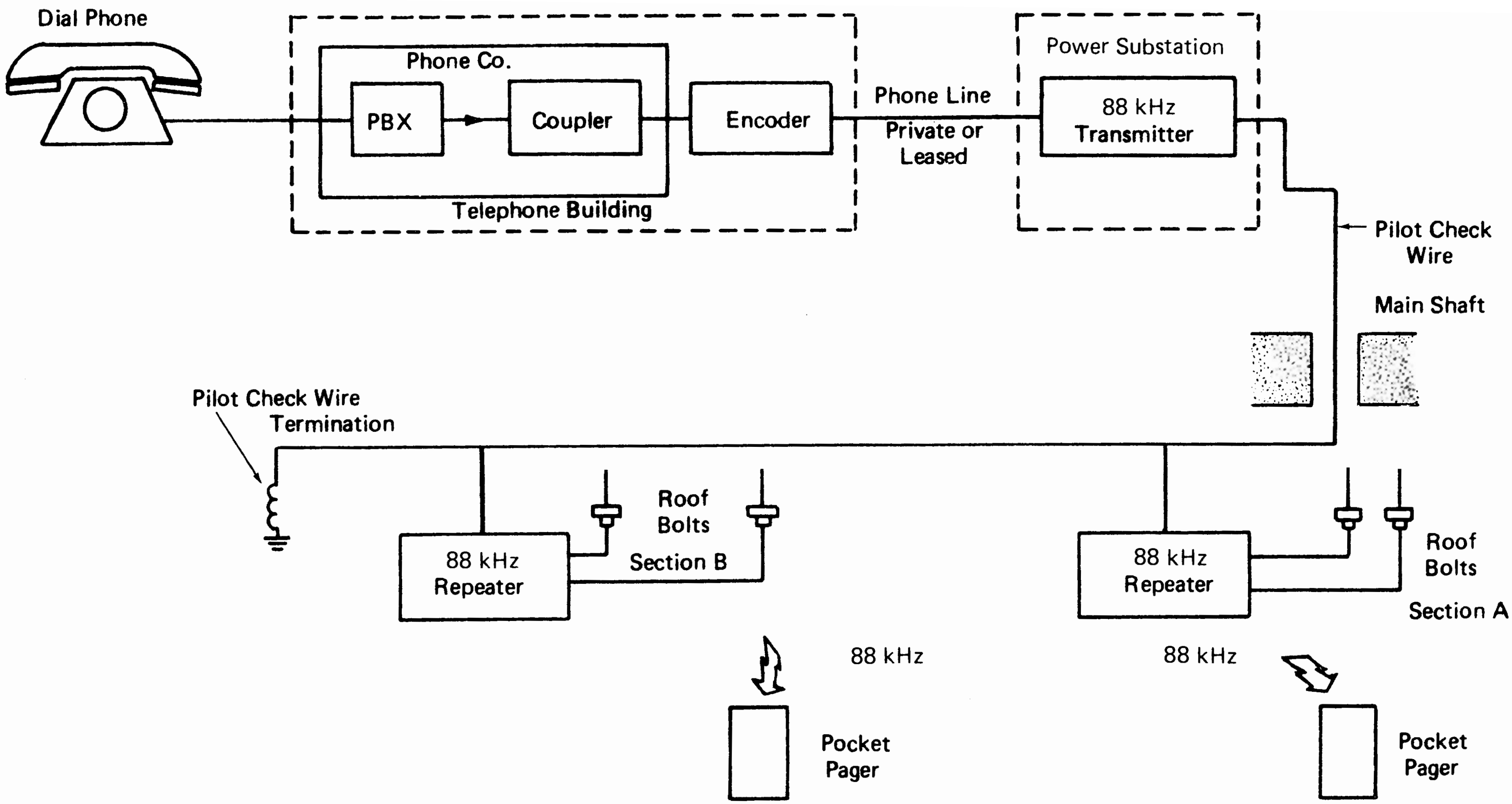


FIGURE 6 WHOLE MINE PAGING SYSTEM

to a Reach encoder which translates his dialed code to the corresponding Reach receiver's code. The signal generated by the encoder is transferred through a private line to a 20 watt 88 kHz transmitter located in the power substation. The 88-kHz transmitter output voltage is connected between the pilot check wire and ground of the power cable that runs down into the mine. In the mine the 88-kHz signal is taken from the pilot check wire and fed through a 20 watt 88-kHz repeater. The output of this repeater is connected to a pair of roof bolts, and the pocket pagers worn by key personnel in the mine respond to their unique pocket-page code. The person calling the page has an opportunity for 10 seconds of message which can be received by the person carrying the pocket pager. In general, it is intended that the person being paged go to the nearest phone in the mine and respond to the request for communication. Figure 6 illustrates two 88-kHz transmitters used to cover two working sections. This number can be expanded to cover each of the working sections in a mine. The principal of operation is the same.

Figure 7 illustrates the installation of the Reach encoder, and Figure 8 shows the 88 kHz transmitter in the mine office. The pilot wire termination is shown in Figure 9, and the underground 88 kHz repeater as shown in Figure 4. Figure 10 illustrates the way in which the pocket pager can be worn.

FIGURE 7. - Reach Encoder Installation.
FIGURE 8. - 88-kHz Transmitter in Mine Office.
FIGURE 9. - Pilot Wire Termination.
FIGURE 10. - Miner Wearing Pocket Pager.

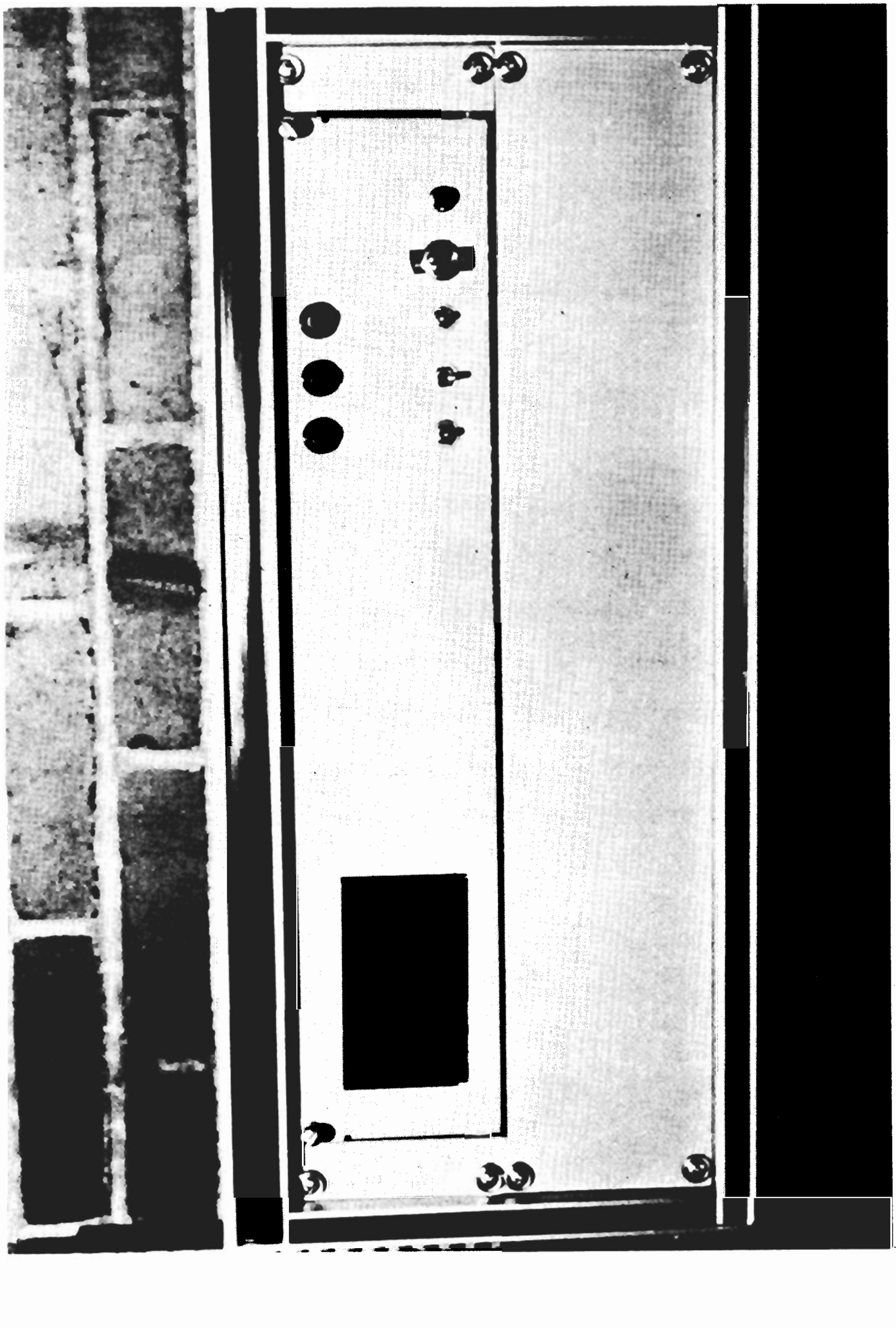

FIGURE 7 REACH ENCODER INSTALLATION

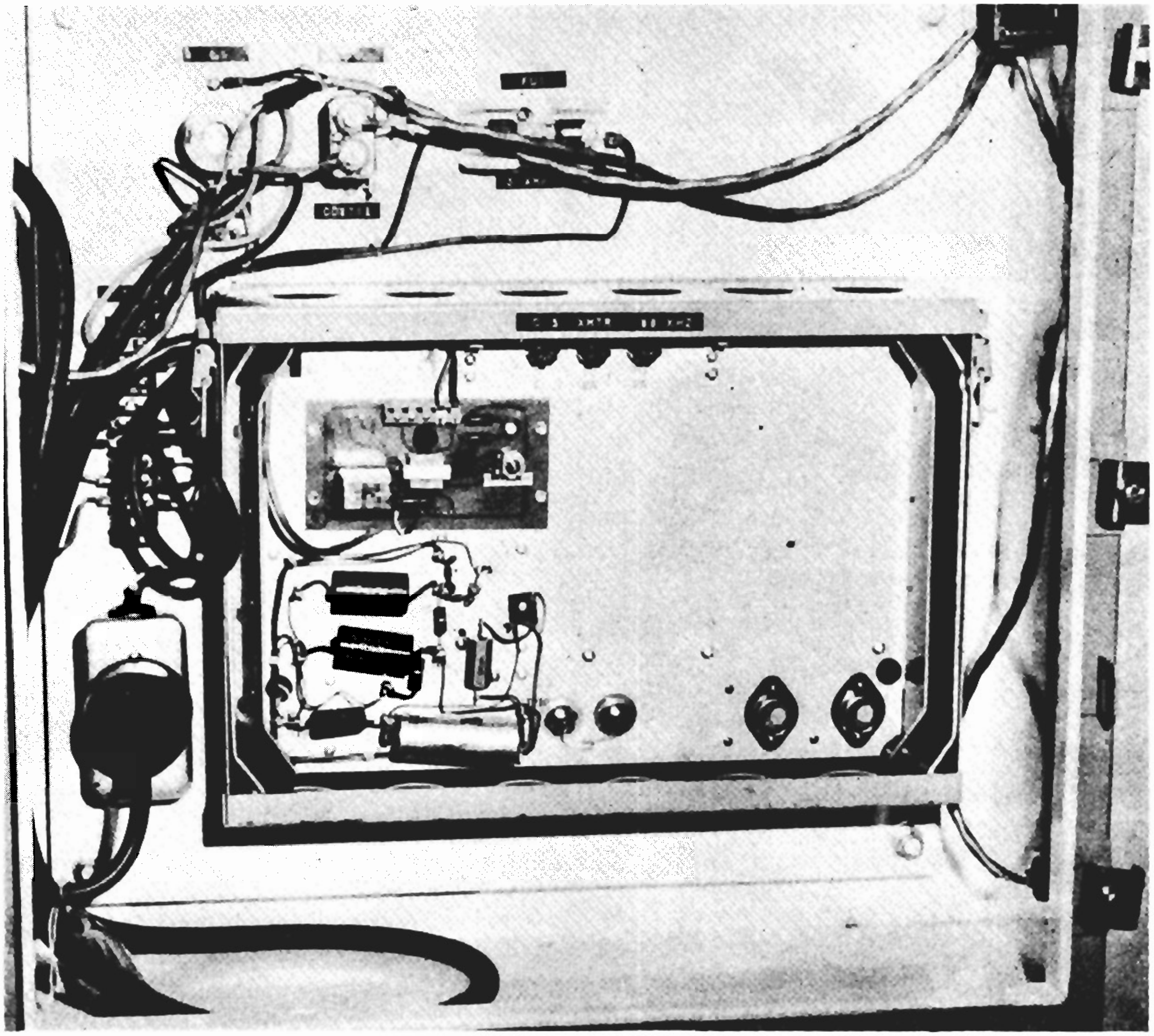

**FIGURE 8 88-kHz TRANSMITTER IN MINE OFFICE**

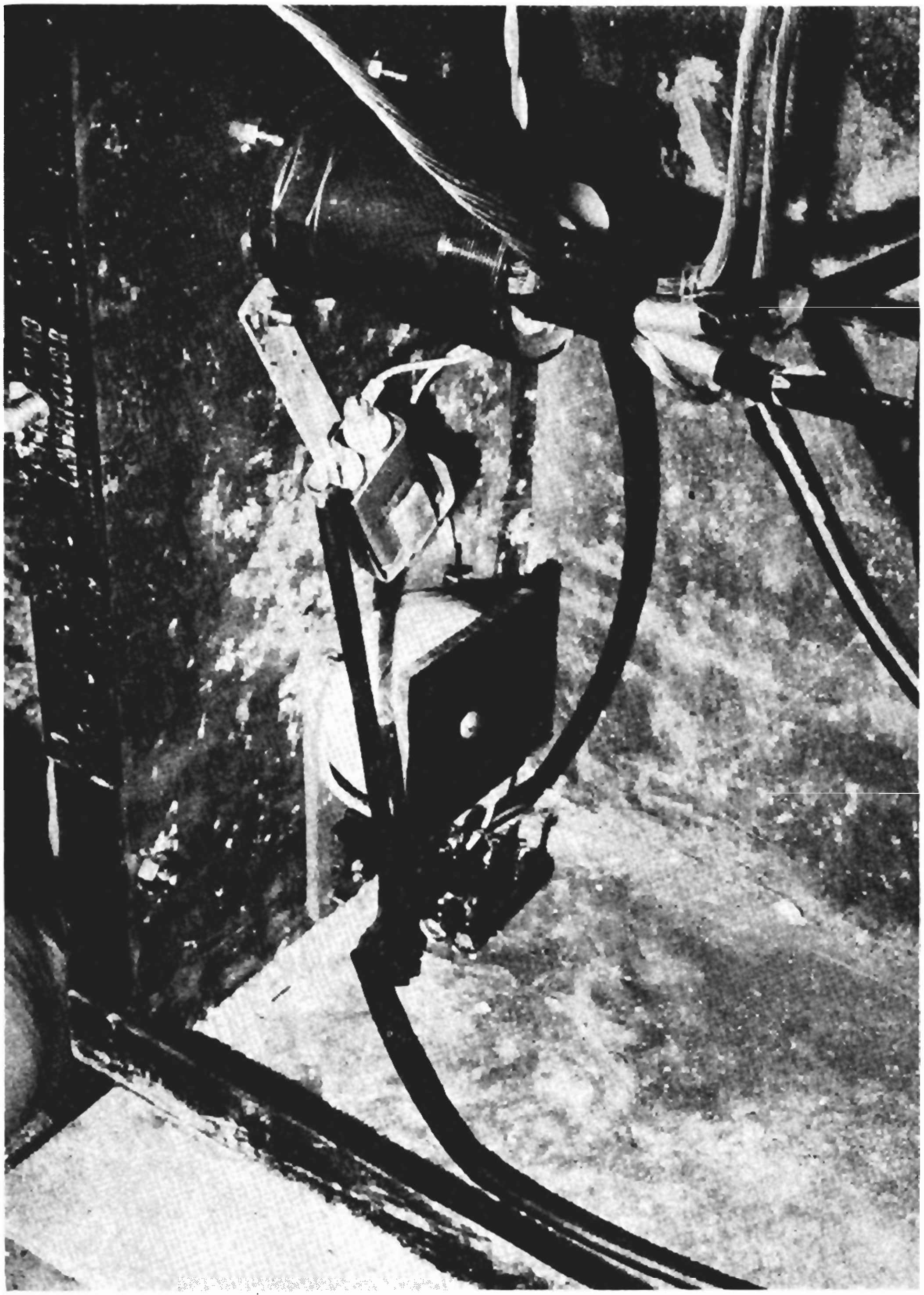

FIGURE 9 PILOT WIRE TERMINATION

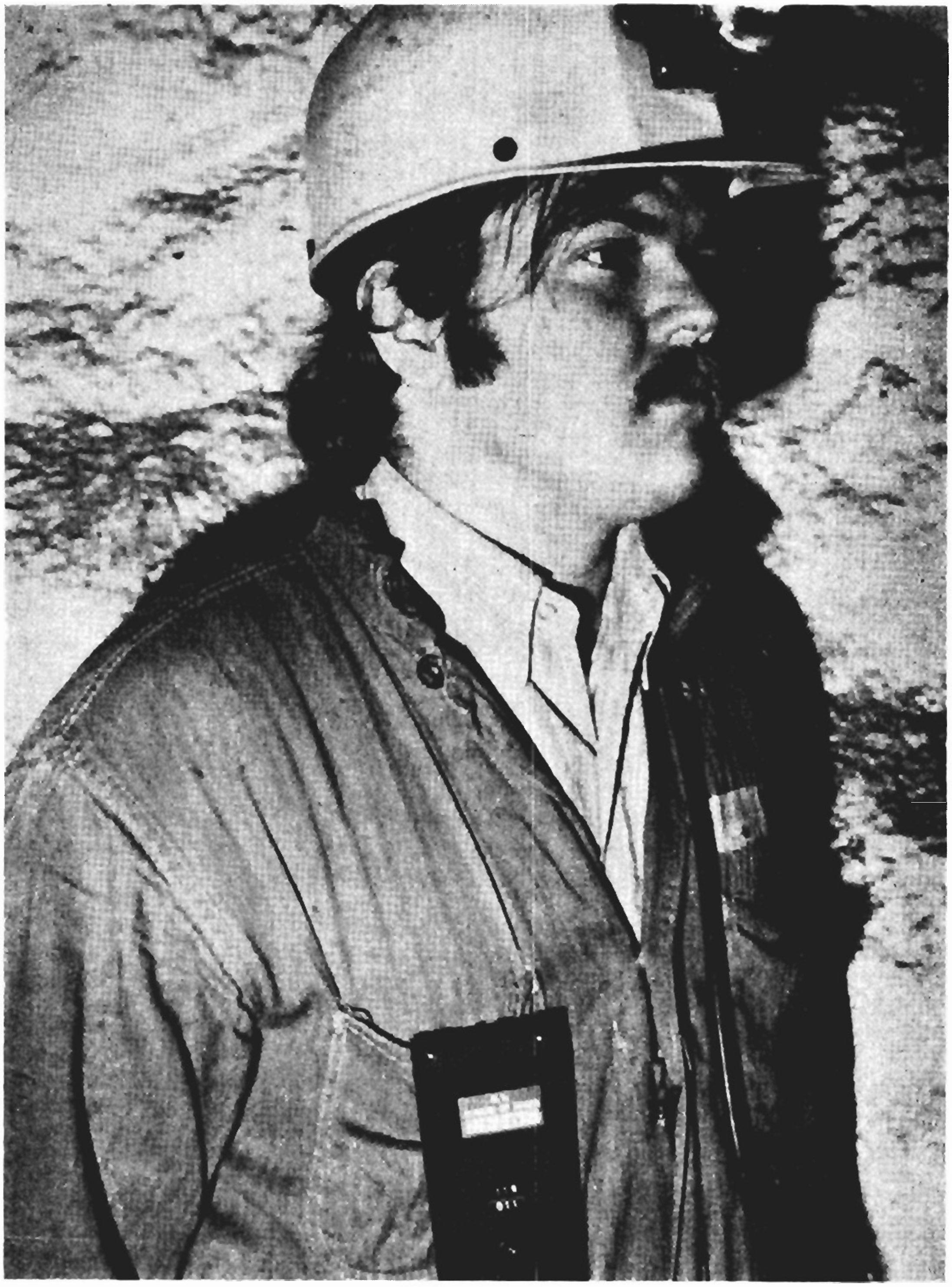

FIGURE 10 MINER WEARING POCKET PAGER

There is a second means of employing paging at carrier frequencies inside the mine. The paging transmitter can be connected to the mine telephone wires, connecting the signal between both wires and ground. The phone wires and ground then become the transmission line for the carrier frequency mine paging system. Once again, repeaters feeding roof bolts can be added in the mine working section area to extend the coverage away from the transmission lines.

The 88-kHz system described above for whole-mine paging has many similarities with the trolley wire carrier communication systems used to dispatch dc haulage vehicles. As such, paging signals placed on the trolley wire can also be extended into the section via the cables of dc face machines connected to the trolley wire power system. Hence, in the vicinity of a trolley wire or trailing cables, a miner with a pocket pager will be able to pick up the page signals via the magnetic fields in the vicinity of these cables. Such an application is illustrated in Figure 11.

FIGURE 11. - Paging on Trailing Cable.

## CALL ALERT PAGING

A special form of paging is commonly called "call alert." It differs from the pocket paging system in that it produces a selective call alert signal that notifies an individual when the mine paging telephone is being used to page him. This system is not capable of as wide an area of coverage as the above roof-bolt paging system; however,

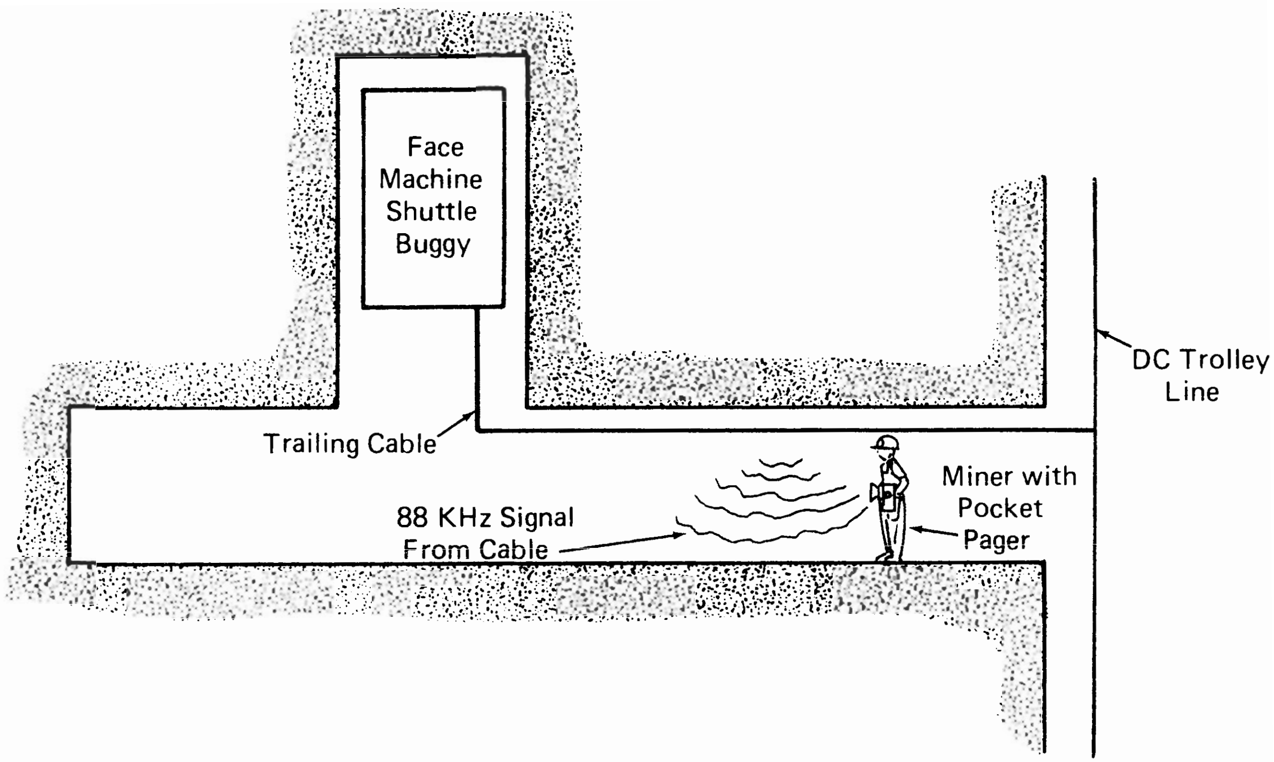


FIGURE 11 PAGING ON TRAILING CABLE

it is very effective in the working section. Once again additional equipment was added to the existing mine communications system. This time the equipment was added to the mine telephone line. A simple transmitter was added in the mine foreman's office and a receiver and call alert transmitter were added in the mine section. The loop antenna of the call alert transmitter was wrapped around a pillar.

In order to receive a call alert, the individual carries a pocket alert receiver. The receiver has a blinking light to indicate a call. From the surface, a non-audible tone is sent over the telephone wires and is received by a selective filter, which in turn energizes the call alert transmitter on the section being paged. Instead of paging over the mine pager telephone system, the paging is personalized to those section individuals carrying the call alert receivers. When the pocket receiver indicates a call alert, the individual walks to the mine pager phone on the section and replies to the page call. This system was developed from work performed in the Bureau of Mines program on electromagnetic detection of trapped miners.

There is an additional benefit to this system. The signal being transmitted on the section is a low-frequency signal that also penetrates the overburden. It has been possible to receive such signals on the surface some 1000 feet above the mine section. Miners on the section can use this transmitter for emergency signaling to the surface. Conversely, the miners can also use the call alert receiver to receive similar operational or emergency transmissions from a surface transmitter.

## Principle of Operation

Figure 12 illustrates a call alert transmitter antenna and its

FIGURE 12. - Call Alert Antenna Illustrating Magnetic Field.

associated magnetic field. The current flowing in the loop produces a magnetic field which links this loop with a small pick up loop in a call alert receiver carried by a person. The operational range of this system is essentially the distance at which the received signals have become small enough for the background noise to interfere with their reception.

## Expected Coverage

Once again, an experiment was done in the Bruceton Experimental mine to determine the efficacy of this system in providing paging coverage throughout a working section. A loop antenna was placed around a coal pillar and driven with a transmitter operating at a frequency of 3030 Hz, and a calibrated receiver tuned to this frequency was carried through the mine to determine the signal strength received at various parts of the mine. The results of these measurements are shown in Figure 13 which illustrates the extent of the call alert coverage. These cover-

FIGURE 13. - Call Alert Coverage.

ages are for a 5-Hz bandwidth receiver. Three contours are shown. The first is for the background noise level found at the Bruceton mine, which we call low noise. It is seen that the coverage provided at a

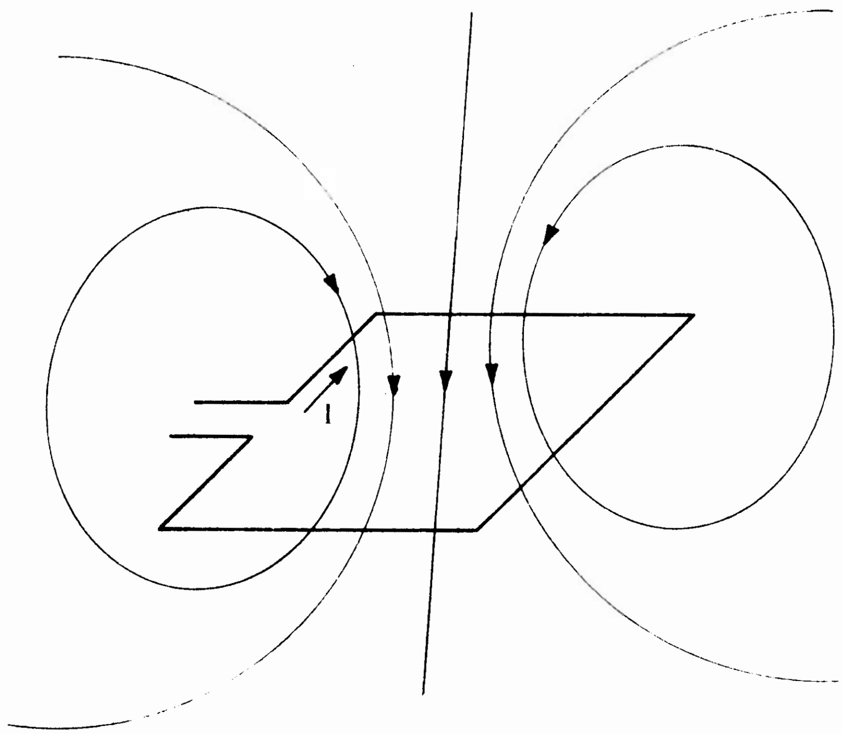


FIGURE 12 CALL ALERT ANTENNA ILLUSTRATING MAGNETIC FIELD

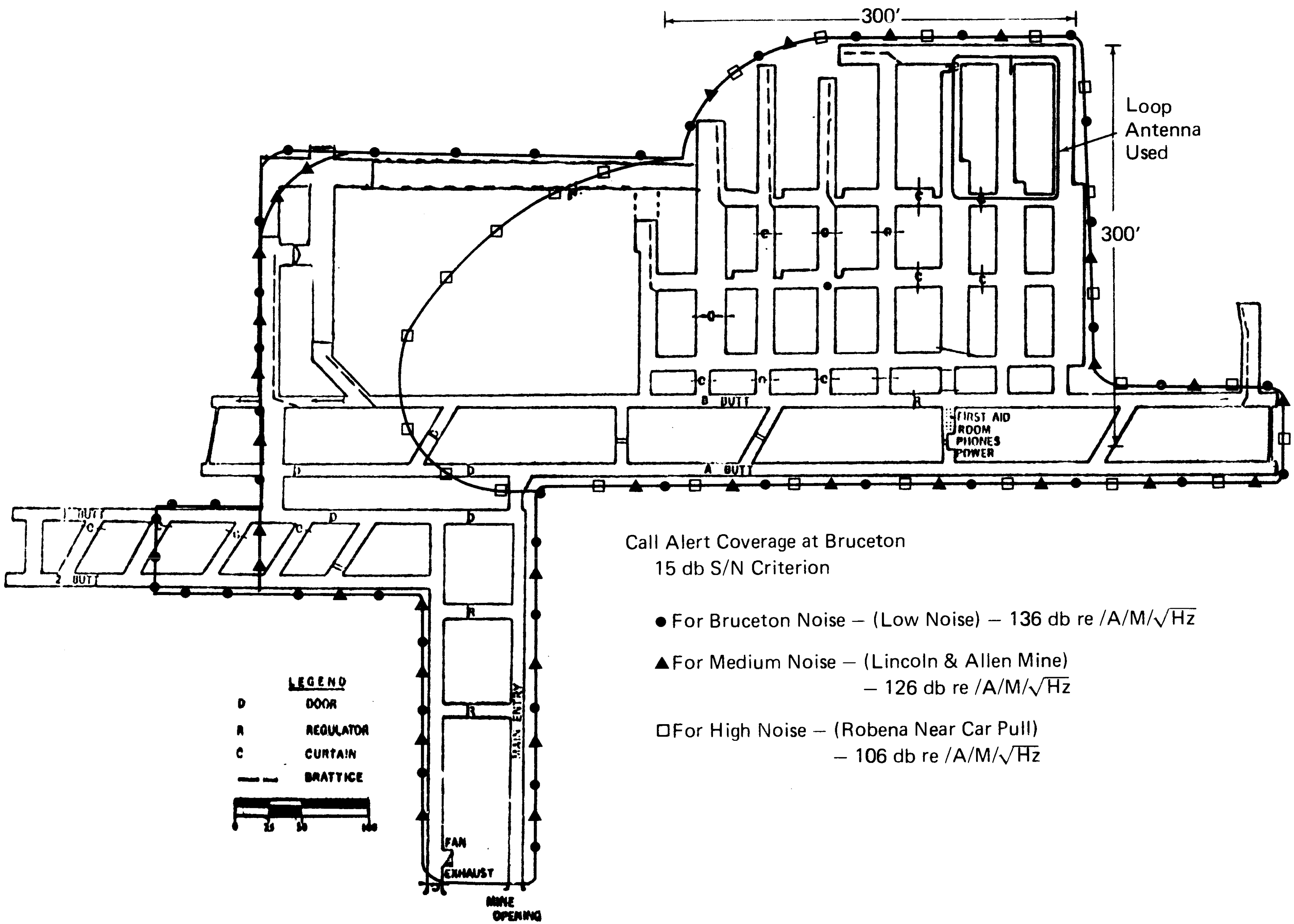


FIGURE 13 CALL ALERT COVERAGE

15-db signal-to-noise ratio extends through most of the mine area, excluding the far extreme left hand corner. Measured noise from operating mines has been used to determine the contours of coverage that would result were such noise levels present in the Bruceton mine. In the medium noise case, a small region of the above coverage is eliminated, while in the high-noise case, a further shrinkage of coverage is observed. The high-noise case represents noise levels measured by NBS at an operating mine near a car pull, and has been identified as the maximum noise condition. Figure 14 shows a photograph of the call alert transmitter and Figure 15 shows a photograph of the call alert receiver. Much like the roof bolt system, coverage over a typical working section can be expected with appropriate positioning of the transmitting loop.

FIGURE 14. - Call Alert Transmitter.
FIGURE 15. - Call Alert Receiver Worn by Miner.

## System Description

The block diagram of Figure 16 illustrates the entire system configuration. A keying transmitter is located in the mine office. To initiate a

FIGURE 16. - Call Alert Paging System.

page, an individual pushes the "press to page" button on this transmitter. This action causes a 19-kHz carrier (other selected inaudible tones can also be used) to be impressed on the mine phone line. This tone enters the mine on the phone line. The keying receiver, attached to the phone

FIGURE 14 CALL ALERT TRANSMITTER

FIGURE 15 CALL ALERT RECEIVER WORN BY MINER

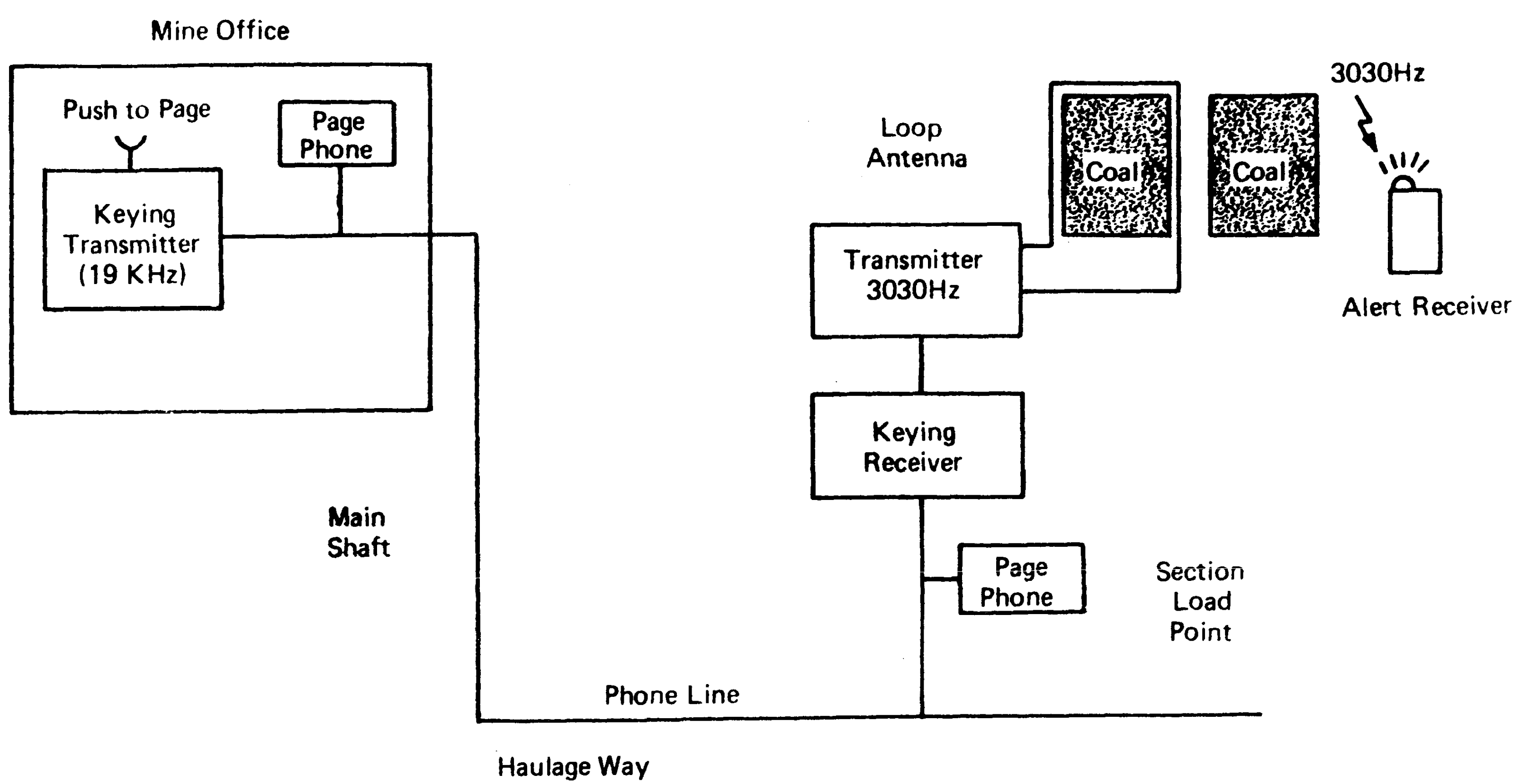


FIGURE 16 CALL ALERT PAGING SYSTEM

line located at a keypoint in a section, responds to this tone. These two units are illustrated in Figure 17. As long as the tone is present,

FIGURE 17. - Keying Transmitter and
Keying Receiver (Control Unit).

the keying receiver connects operating power to the call alert transmitter connected to the pillar mounted loop. In the present system this call alert transmitter drives a 3030-Hz signal current into the loop antenna of the system, thereby producing a 3030-Hz signal that penetrates to all regions of the section. A pocket-sized call alert receiver incorporating a small pick-up loop is carried by a person roving through the section. This receiver responds to the presence of the 3030-Hz signal by flashing a light on the receiver or by generating an audio alert signal. The person paged is thus notified to call the mine office.

A word of caution: Call alert systems use carrier signals over the telephone wires. A preliminary examination of several of the mine pager telephones indicates that these phones are not fully compatible with the normal range of telephone grade carriers. We are now investigating this problem and anticipate that a simple add-on device (applique) can be made for installation on existing mine pager phones to make them compatible with carrier applications. At this time, it is possible that some carrier frequency systems will require excessive amounts of power if utilized on present mine telephone installations.

## CONCLUDING REMARKS

The emphasis of our paging efforts has been placed on the extension of existing mine communications to improve their utility under operational and emergency conditions. Primarily we have been concerned with extending the page message from the equipment that receives the page to the

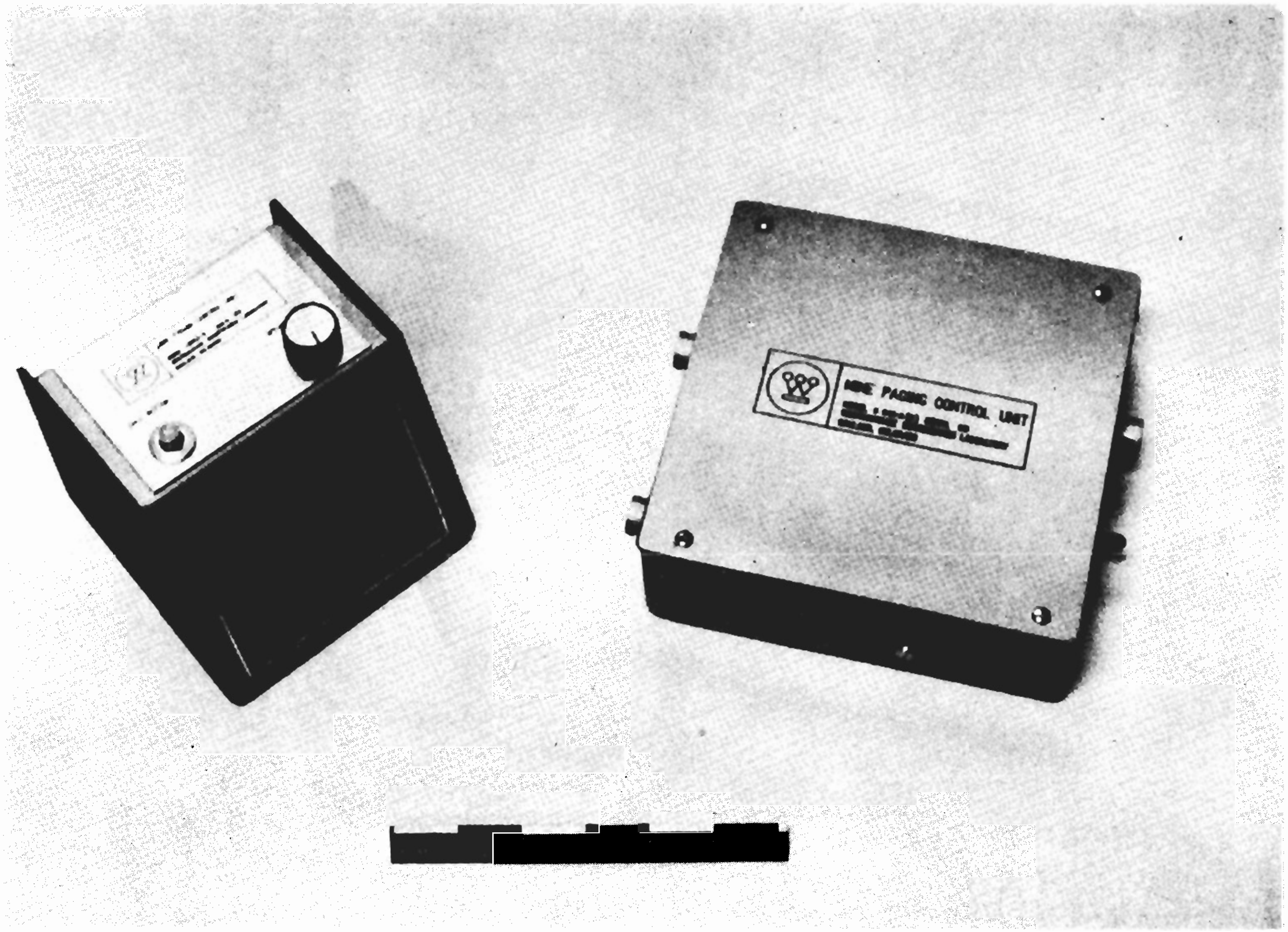


FIGURE 17 KEYING TRANSMITTER AND KEYING RECEIVER (Control Unit)

person who is being paged. Paging can also be added to wireless radio communication systems; however, there are very few mines currently using wireless radio. The objective in paging is to alert a person that he is wanted on the telephone. The person replying to the page will generally not reply over the same channel by which he was paged. The paging system and the call alert system discussed here meet different needs. The general features of these two systems are summarized in Table 1.

TABLE 1. - Roving miner paging

| | Roof bolt system | Call alert system |
|---|---|---|
| Coverage | Part or whole mine | By section |
| Voice page | Yes | No |
| Selectivity | To individual | To section |
| Emergency use | Not practical | Yes |
| Equipment availability | Current | 60 Days |

## C. TWO-WAY COMMUNICATIONS WITH ROVING MINERS

by

Robert L. Lagace[1] and Howard E. Parkinson[2]

### ABSTRACT

UHF wireless and guided wireless radio systems are operational in the U.S. Bureau of Mines Safety Research Mine in Bruceton, Pa. The systems satisfy the need for instant personal two-way communications between key individuals roving in working sections and haulage ways, and between these individuals and the surface. The individuals are equipped with portable handy talkie radios that are Bureau-approved for operation in a gassy mine. The Bureau's systems operate at 420 MHz, a frequency allocated to government users. Systems belonging to industrial users such as mines can utilize the 450-470 MHz UHF band allocated to industrial land mobile applications. The UHF band is more effective than the VHF band for unaided propagation in the sections and haulage ways of mines.

The UHF wireless radio system does not need any special guiding cables, and is particularly attractive for mine section applications, as well as haulage ways. The UHF guided wireless radio system is based on

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1 Arthur D. Little, Inc., Cambridge, Mass.

2 Supervisory Electrical Research Engineer, Industrial Hazards and Communications, Pittsburgh Mining and Safety Research Center, Bureau of Mines, U.S. Department of the Interior, Pittsburgh, Pa.

the use of a special radiating coaxial cable installed along main entries, and is suitable for haulage way applications. This paper treats the principles of operation, expected communication ranges, and the key features and limitations of both systems.

## INTRODUCTION

### Need for Two-Way Communications with Roving Miners

Historically, communication equipment for underground mine use has been based on "wired" systems, namely, the loudspeaking mine telephone system and the trolley wire carrier phone system. The mine telephone system includes both magneto phones and loudspeaking telephones, while the trolley wire carrier phone system utilizes carrier current transmitters and receivers. In both cases all the transmitting and receiving equipment is "hard wired" to the telephone line or to the trolley wire, respectively. As such, this equipment is not portable. Therefore, it is inadequate for paging or communicating with key individuals, such as foremen and maintenance men, when they are not in the immediate vincinity of the communication equipment.

The roving miner paging systems recently developed by the Bureau of Mines and discussed in a companion seminar paper, meet the need to deliver one-way paging messages and call alerts to key individuals on-the-move in the mine. These are messages or alerts that the paged individual must either act upon, or acknowledge via another communications channel in the mine. However, situations also arise in which an instantaneous and continuing response from key roving miners is either essential or extremely desirable from an operational or safety point of view. The ability to reach and talk with an individual where he happens to be, and not only at a limited number of fixed stations, is particularly beneficial when:

- downtime can be reduced by permitting individuals working on machinery to communicate with surface supervisors without leaving the machinery; or
- the message is urgent and the individual is on-the-move underground.

Two-way wireless and guided wireless radio systems recently investigated by the Bureau can provide this personalized instantaneous communication to individuals over important parts of the mine.

## Two-Way Wireless Radio in Mines

The thrust of our two-way wireless radio communication work has been to extend two-way communications to key miners roving within the section and in the haulage way. The principal objective has been to find ways in which commercially available, portable radio equipment can be adapted for practical use in operational coal mines.

Electromagnetic waves at radio frequencies are not capable of penetrating the overburdens of typical mines because of the severe attenuation suffered in the overburden by the waves at these frequencies. To utilize radio waves in mine entries and cross-cuts, the radio signal sources must be brought into the mines and to the areas of interest, either directly or via guiding cables or wires.

The operating frequency is a key factor that significantly influences the communication range of any wireless radio system in mines. American coal mining methods require area coverage, as opposed to the linear haulage way coverage that is typically needed for European longwall mining. By area coverage we mean communications throughout a working section that may typically encompass an area 600 feet x 600 feet, and communications down cross-cuts to several hundred feet away from the main haulage ways.

We have found that frequencies in the UHF band offer the best area coverage for completely wireless two-way voice communications between portable handy talkie radios. This we have determined from theoretical considerations backed up by in-mine experiments. Two-way wireless communication ranges between hand-held units in mine entries are limited to approximately tens of feet at citizens' band frequencies near 30 MHz; are extended to several hundreds of feet at VHF band frequencies around 150 MHz; and are further extended to over 1500 feet for UHF band frequencies around 450 MHz. These ranges apply to straight line communications along an entry, and are reduced if corners are present in the transmission path. In addition to offering the greatest promise for extending two-way communications to roving individuals, the 450 MHz UHF frequency band is presently the upper limit for commercially available portable radio transceivers. This frequency band has also been receiving much publicity and interest in the underground mining industry.

Two specific UHF radio communication systems are treated in this paper. The first is truly wireless and particularly attractive for section applications, so it has been named UHF wireless section radio. The second makes use of a special coaxial cable for guiding and radiating UHF radio waves along mine entries, so it has been named UHF guided wireless radio.

## UHF WIRELESS SECTION RADIO SYSTEM

Two-way wireless section radio systems can provide communications between key individuals who may be working at different locations within a section, and between these individuals and the surface. These systems can also be applied to haulage way communications. Figure 1 gives an overall view of such a system for a section application. It is described in detail under System Description, after discussion of the system's principles of operation and expected communications coverage.

Figure 1. - Two Way Wireless Section Radio System

### Principles of Operation

Figure 2 depicts in schematic form a UHF radio wave propagating down a coal mine entry (tunnel), *without* the assistance of any metallic guiding wires or cables. At VHF/UHF frequencies, the entries themselves behave like "leaky" waveguides, guiding the signal energy along the length of the entry, while also losing part of the energy to the

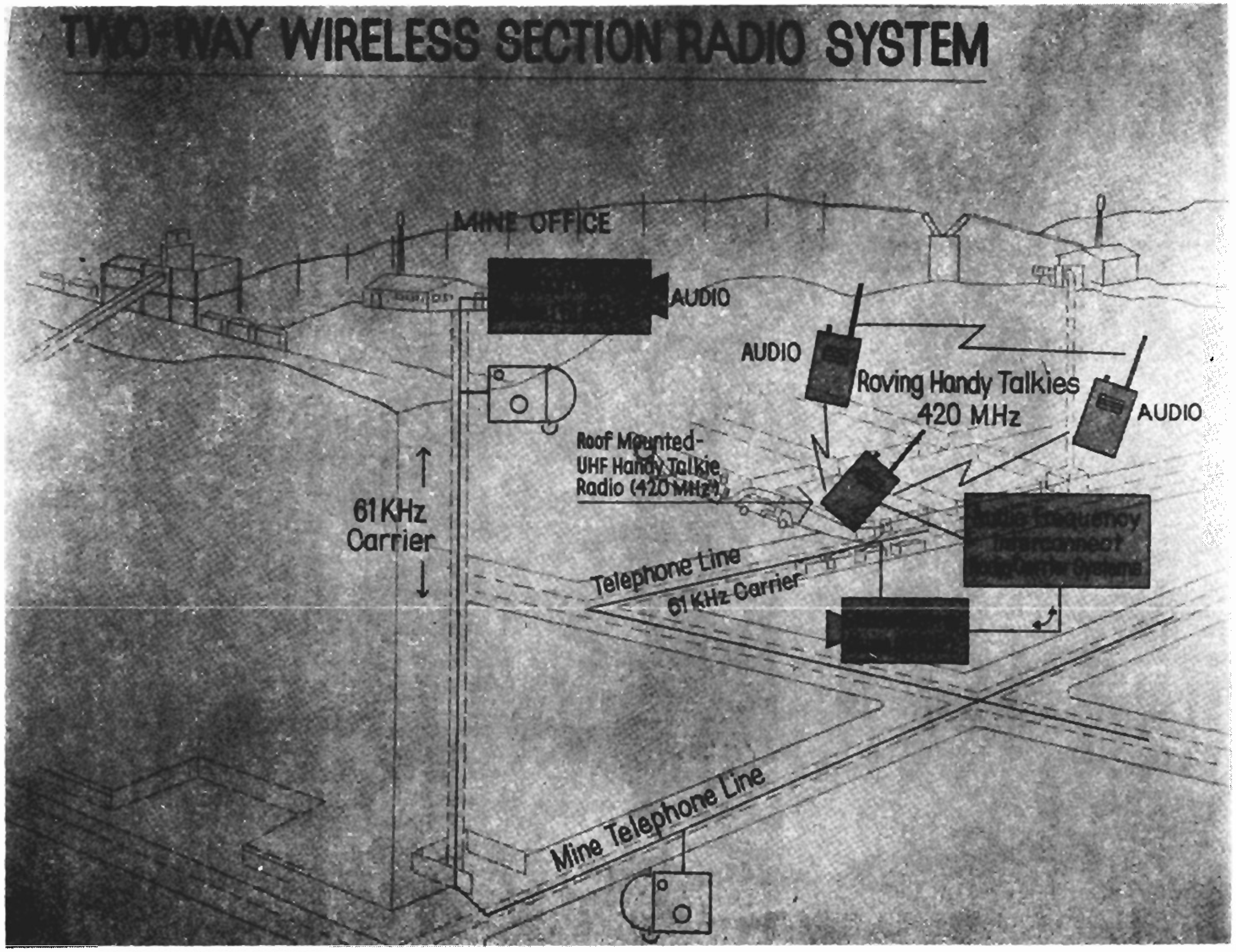


FIGURE 1 TWO-WAY WIRELESS SECTION RADIO SYSTEM

surrounding medium. By analogy, the roof, floor, and walls of a mine entry can be considered as imperfect mirrors and the radio waves as light beams. As the light beam, or radio wave, travels down the mine entry, bouncing off the walls, roof and floor, part of its energy is reflected at each bounce and therefore retained in the entry, while part of its energy is transmitted into the coal or rock by refraction and therefore lost.

Figure 2. - UHF Wireless Radio in Coal Mines.
Principle of Operation.

Figure 3 illustrates how the signal attenuation loss for mine entries varies with operating frequency for the dominant propagating mode. This loss represents the fractional decrease in strength, expressed in decibels (dB), suffered by the signal for each 100 feet it propagates down the entry. The curves in Figure 3 are based on data from propagation experiments performed in an operating high-coal mine, and on values calculated from theoretical equations. As shown, both theory and experiment indicate that: in high-coal entries, wireless radio signals are attenuated severely below the UHF frequency range, experience a broad favorable minimum in attenuation between 500 MHz and 2,500 MHz in the UHF band, and finally suffer a gradual increase in attenuation as the frequency is increased beyond the UHF frequency band. In low-coal the attenuation loss is shown to be more severe, particularly below 1,000 MHz. This low-coal behavior has only been partially confirmed by the routine use of 420 MHz handy talkies during field trips to mines.

Figure 3. - UHF Wireless Radio Signal Attenuation Loss
in Coal Mine Entries

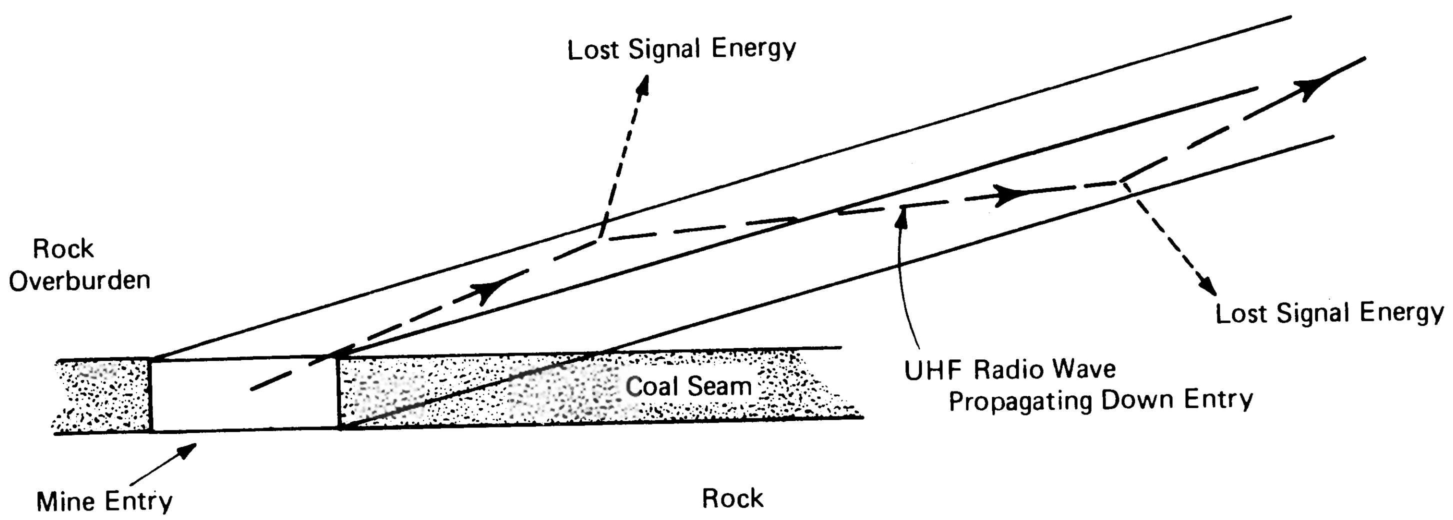


**FIGURE 2 UHF WIRELESS RADIO IN COAL MINES – PRINCIPLE OF OPERATION**

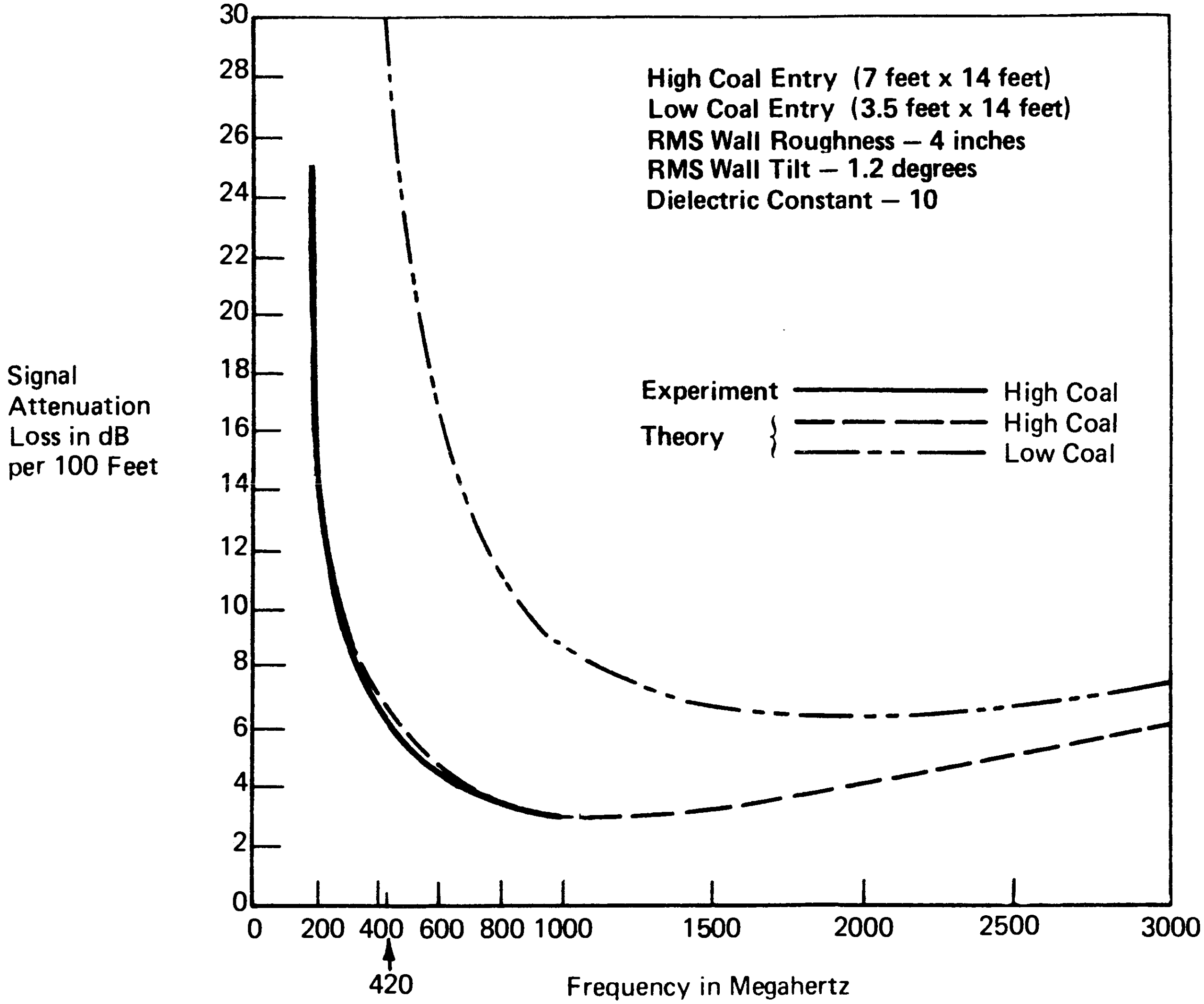


FIGURE 3 UHF WIRELESS RADIO SIGNAL ATTENUATION LOSS IN COAL MINE ENTRIES

The other major frequency dependent losses are antenna coupling loss and corner loss. When they are added to the attenuation loss, the appearance of an optimum operating frequency band becomes more pronounced. In high-coal, the optimum band is 400-to-1000 MHz. Within this band, the best frequency for a particular application will depend on the desired communication distance and whether the signal must travel around a corner to reach the receiver. For example, operating frequencies near 400 MHz are favored for transmission paths about 500 feet long that include one corner. Such paths are typical for section applications. Frequencies near 1000 MHz are favored for long straight line transmission paths along haulage ways.

The Bureau has tested portable mobile radio equipment up to the present frequency limit of equipment availability, the 450-MHz band, the band which also offers the most favorable performance for section applications in high-coal. Allocation of a new band of frequencies around 960 MHz for land mobile industrial applications is presently under consideration by the FCC. However, portable and fixed station 960 MHz equipment for haulage way applications will still not be commercially available for several years. Therefore our present investigations and range predictions were concentrated on the 450 MHz band.

## Expected Coverage

Communication can be maintained between two separated individuals or stations until the separation distance increases to a point where the signal strength is not sufficient to overcome the background electrical noise. At UHF frequencies, measurements have shown that the levels of this background noise will be governed by the intrinsic electrical noise of the UHF receivers rather than by externally generated electrical noise in the mine. The wireless radio coverage of a typical section in high-coal has been estimated for Motorola HT220 FM handy talkie units operating at a frequency of 420 MHz. These portable units have a transmitter power of two watts and receiver sensitivity of 0.5 microvolt for 20 dB of quieting.

Since communication on a working section requires coverage down cross-cuts, one must add to the straight line attenuation the loss incurred by the signal in going around at least one 90° corner. At 420 MHz, theory and experiment support the use of a corner loss of about 58 dB for the dominant propagating mode. To these losses must be added a total antenna coupling loss of about 46 dB to account for the insertion, polarization, and efficiency losses expected for two portable handy talkies. A nominal signal fade margin of 12 dB should also be included. The above values lead to the conservative section coverage prediction shown in Figure 4.

Figure 4. - Predicted UHF Wireless Radio Coverage

Figure 4 illustrates the coverage expected in a high-coal mine between a centrally located miner with a handy talkie unit and a second miner roving throughout the section with another unit. Miner-to-miner separation of more than half a section is possible, unaided by any transmission lines or other guiding cables. This separation can be doubled to cover the whole section by placing a repeater unit at the central location in the section.

Frequency – 420 MHz

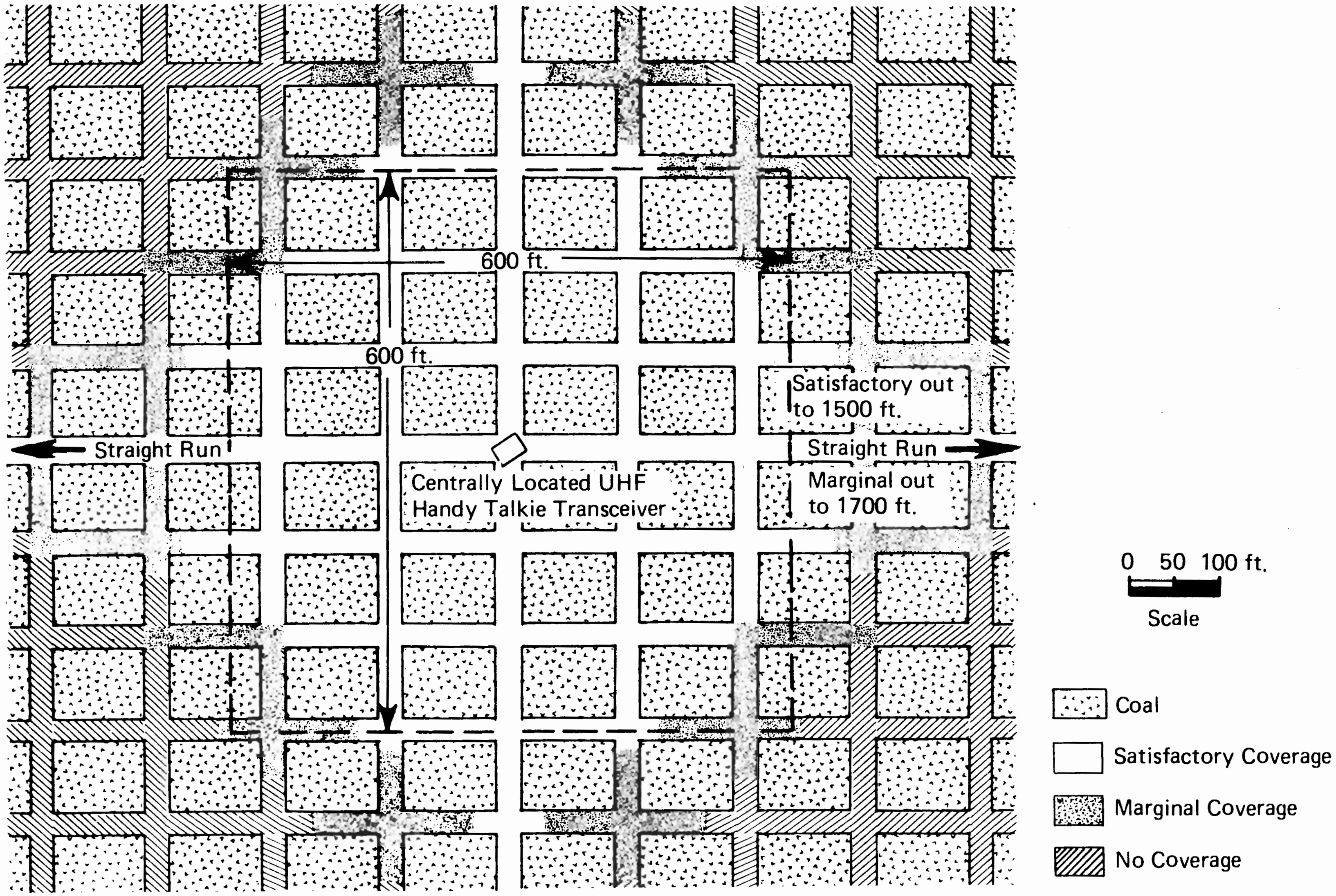


FIGURE 4 PREDICTED UHF WIRELESS RADIO COVERAGE

Note that when the signal must go around only one corner, satisfactory communication can be expected over a linear distance of approximately 500 feet down an entry and cross-cut. When no corners are encountered, as in a haulage way transmission path, satisfactory straight line communication can be expected over distances in excess of 1500 feet. These range limits can usually be somewhat extended if the handy talkies are rotated into the horizontal plane and pointed across the entry, thereby taking full advantage of the dominant horizontal field component. Practical ways to further extend section coverage, by reducing the relatively high corner loss, are presently under investigation.

Figure 5 represents a coverage diagram obtained for a portion of the Bureau's Safety Research mine at Bruceton. The coverage experienced in the Safety Research mine supports the coverage predictions of Figure 4. In Figure 5 the transmitter is located in the upper right-hand corner, and the coverage represents roughly one quadrant of a working section as indicated by the dimensions. The other three quadrants will experience the same coverage. Note that when the signal has to go around one corner, the coverage is as predicted, but that two corners produce a quick transition to unsatisfactory performance. The coverage to the left of Figure 5 does not extend beyond 200 feet because of the absence of a connecting cross-cut. Also depicted in Figure 5 are the main elements of the wireless section radio system installed in the Safety Research mine. This system will be described in the next part of this paper.

Figure 5. - UHF Two-Way Wireless Section Radio Coverage In the Safety Research Mine

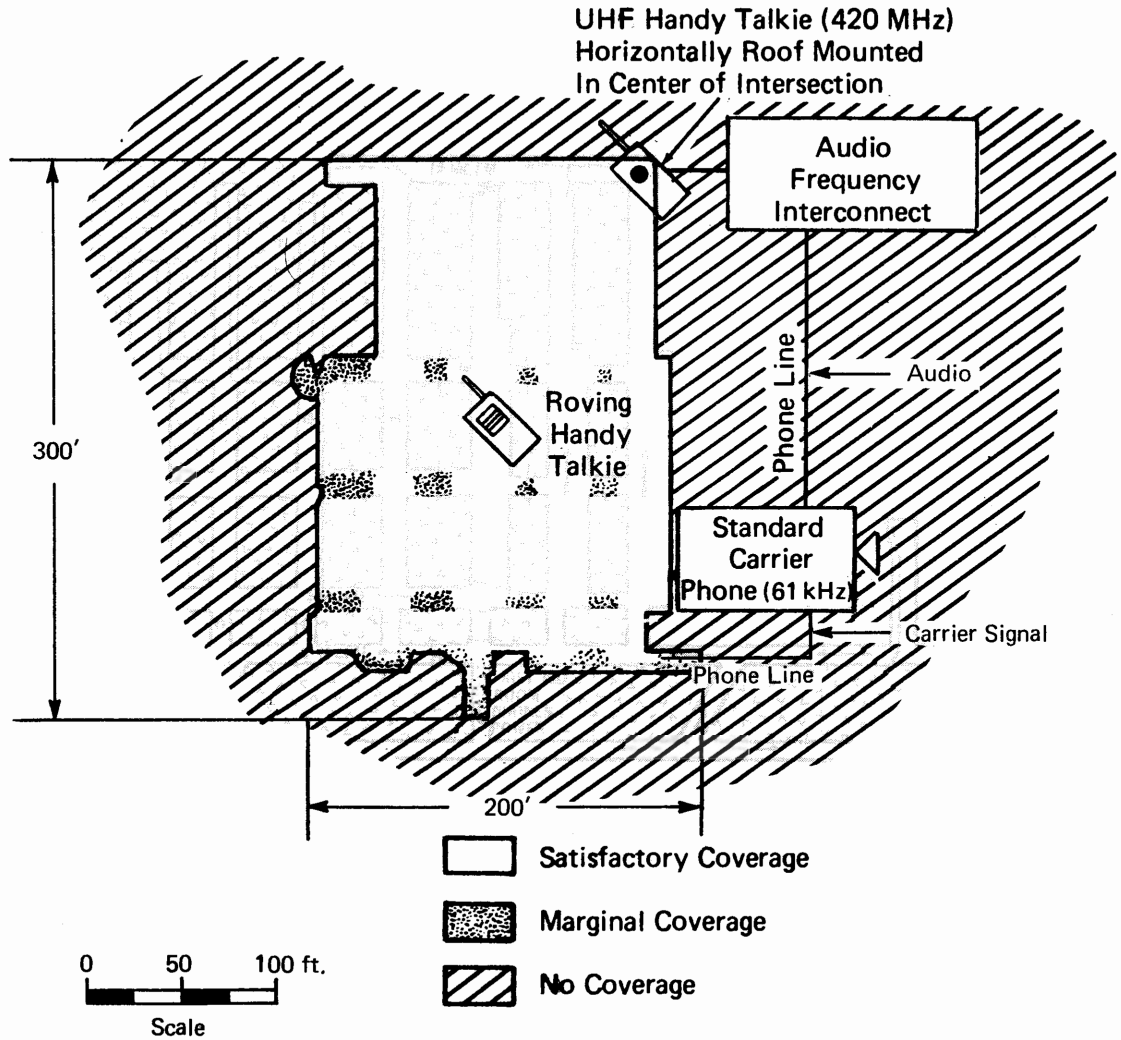


FIGURE 5 UHF TWO-WAY WIRELESS SECTION RADIO COVERAGE IN THE SAFETY RESEARCH MINE

## System Description

An overall block diagram of a wireless section radio system is shown in Figure 6. Roving miner-to-miner direct wireless communication within the section is obtained by using channel two on the portable handy talkie units. In this direct mode of operation, the portable units transmit and receive on channel two. The system also provides roving miner communication with the surface on this same channel. This is accomplished by the use of a special interconnect unit which is roof-mounted with another handy talkie in an intersection at a centrally located position in the section. This radio-to-carrier system interconnect unit couples the audio frequency portion of the roof-mounted UHF handy talkie to the audio frequency portion of a 61 kHz standard miner carrier phone that is attached to the mine telephone line. In the mine office at the other end of the mine telephone line is a corresponding carrier phone unit which completes the mine-to-surface communication link. A conversation can be initiated from either the mine office or the roving miner on the section by simply using the mine office carrier phone or the portable handy talkies in their standard modes of operation. The system described provides an instantaneous direct private line to key roving miners on a section, even when the mine telephone line is busy with normal audio frequency communication traffic.

Figure 6. - Two-Way Wireless Section Radio System Block Diagram

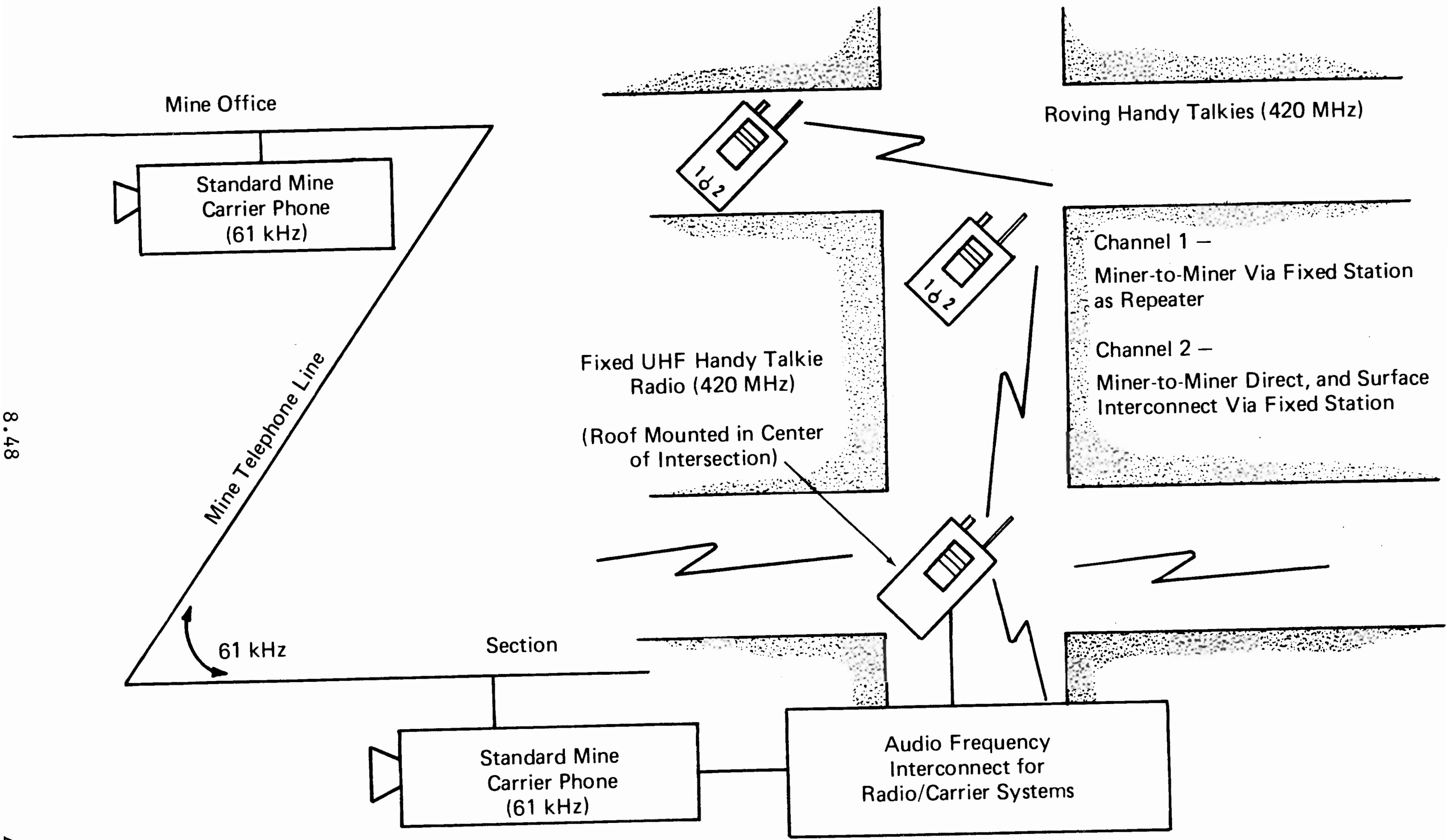


FIGURE 6 TWO-WAY WIRELESS SECTION RADIO SYSTEM BLOCK DIAGRAM

As stated in the coverage discussion, the roving miner-to-miner communication range can be doubled, thereby extending roving miner coverage to the whole section by using a roof-mounted repeater at the central location. To operate in the repeater mode, miners would switch to channel one. In this repeater mode of operation, the portable units transmit on channel one but still receive on channel two. This allows a centrally located repeater station to pick up the channel one transmissions of the miners and rebroadcast them on channel two for subsequent reception by the other handy talkies, thereby doubling the miner-to-miner range of the system.

Another benefit is obtained when in the repeater mode. Namely, roving miner-to-miner communications traffic will not clutter the section-to-surface interconnect channel, but messages from the surface will still be receivable by the roving miners.

Figure 7 shows a Motorola HT220 intrinsically safe handy talkie unit attached to a miner's belt. Operation can be via a push-to-talk switch and speaker-microphone that is an integral part of the handy talkie unit. Alternatively, the switch and speaker-microphone can be in the form of a hand-held accessory as shown in Figure 7. This accessory can be conveniently clipped to a pocket or lapel. Operation is also possible by means of a bone conductance microphone and ear speakers attached to the miner's hardhat as shown in Figure 8. The bone conductance microphone is situated in the middle of the hardhat webbing so that it can pick up the skull vibrations created when a person speaks. The ear speakers are put close enough to the ears to hear the received audio while still leaving the ears open to the normal sounds in the mine. This hardhat unit can be operated by a belt-mounted push button as shown in Figure 8, or by means of a voice-operated switch which keys the transmitter on whenever the person speaks. This allows completely hands-free operation. Figure 9 depicts a handy talkie unit installed in a roof-mounted radio-to-carrier surface interconnect unit fabricated by Collins Radio Co. This station is typically mounted horizontally at a 45-degree angle in an intersection centrally located in the section. The cabling on the left goes to a standard mine carrier phone attached to the mine telephone line.

Figure 7. - Miner Using Intrinsically Safe Handy Talkie Unit

Figure 8. - Handy Talkie Operation Using Hardhat with Ear Speakers and Bond Conductance Microphone

Figure 9. - Roof-Mounted Radio-to-Carrier Surface Interconnect Unit and Handy Talkie Unit

The basic system depicted in Figure 6 can be used in a variety of ways and circumstances. It can be used to extend two-way communications between key roving miners within a section, and between these miners and the surface. The system can be used to communicate with roving miners along any haulage way having a mine telephone line by placing interconnect and repeater stations similar to those for sections at approximately 0.6 mile intervals along the haulage way. The system with the surface interconnect also lends itself to installation and use as a temporary surface-to-roving miner communication link during maintenance or rescue operations. Finally, this particular system can be modified for use with less expensive pocket pagers, instead of handy talkies to provide a more limited call alert or paging mode of operation.

FIGURE 7 MINER USING INTRINSICALLY SAFE HANDY TALKIE UNIT

FIGURE 8 HANDY TALKIE OPERATION USING HARDHAT WITH EAR SPEAKERS AND BONE CONDUCTANCE MICROPHONE

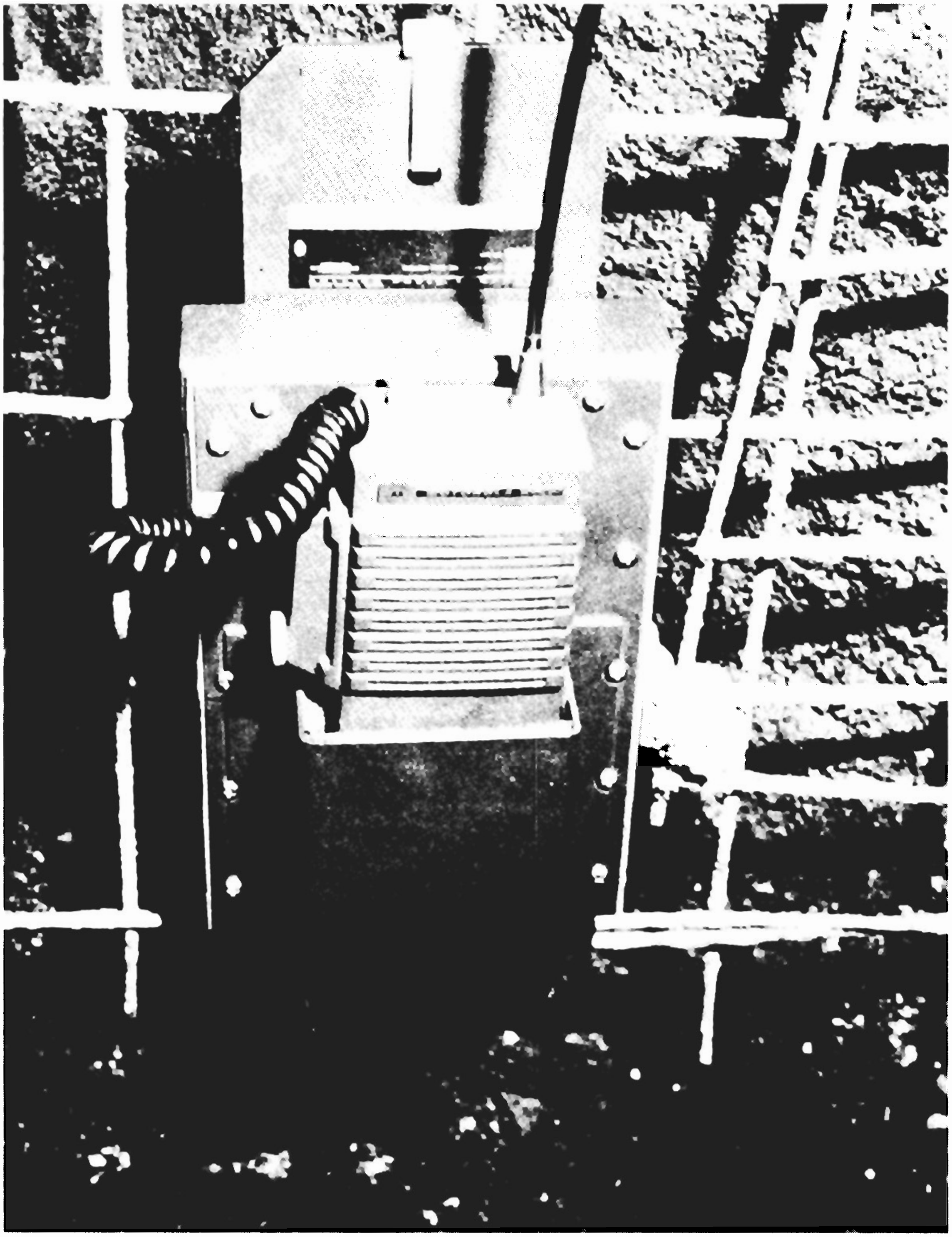

FIGURE 9 ROOF-MOUNTED RADIO-TO-CARRIER SURFACE INTERCONNECT UNIT AND HANDY TALKIE UNIT

## UHF GUIDED WIRELESS RADIO SYSTEM

The second UHF radio system treated in this paper is the guided wireless radio system. This system can provide communications between key individuals who may be roving at different locations along or near haulage ways, and between these same individuals and the surface. As in the wireless section radio application, the key roving individuals carry portable handy talkie radio transceivers. However, unlike wireless section radio, guided wireless radio uses a special cable to pick up, transport (guide), and radiate the radio frequency energy along haulage ways and main entries to communicate with the portable handy talkies. Figure 10 gives an overall conceptual view of a roving miner two-way haulage way communication system based on the guided wireless radio concept at UHF frequencies. As illustrated, such a system operating at UHF requires that a special cable (Radiax T.M. in this case) and auxiliary lines be hung along the walls of the haulage ways and selected section entries, together with periodically spaced repeater or base stations. The system will be described in detail under System Description.

Figure 10. - Guided Wireless Radio System

The UHF Radiax cable system was investigated because it has been receiving increased publicity and attention by the equipment suppliers and mine operators, and because of the favorable propagation characteristics at UHF for the area coverage desired in American coal mines. However, our investigations indicate that the desired area coverage is not achievable in an economical manner with Radiax cable. Furthermore,

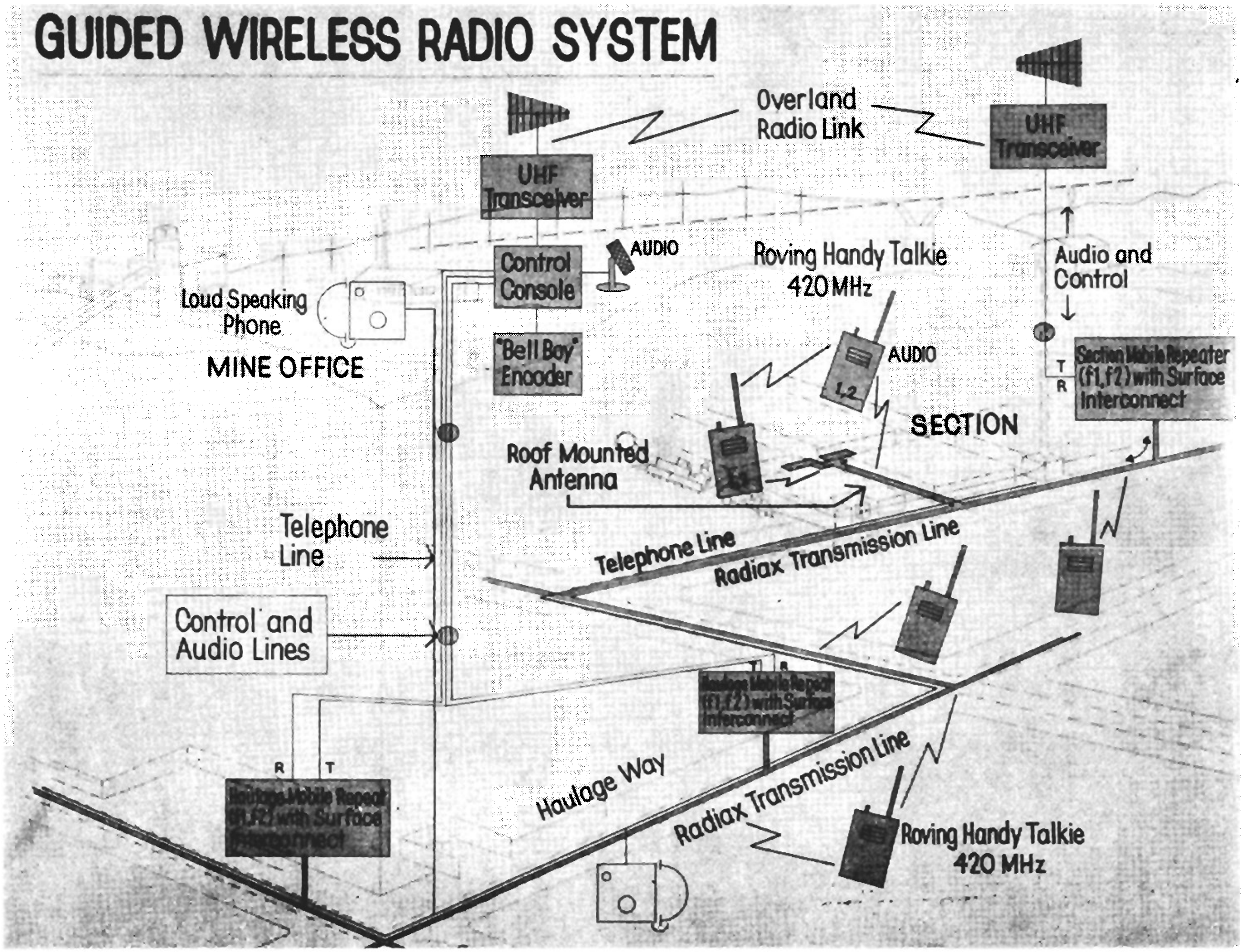


FIGURE 10 GUIDED WIRELESS RADIO SYSTEM

much lower frequencies can be effectively used with more economical guiding cables if the desired communications can be restricted primarily to the haulage ways as in Europe.

## Principles of Operation

Figure 11 depicts in schematic form a cross-section view of a coaxial cable and the lateral variation of its associated fields. In such cables the bulk of the radio frequency electromagnetic energy is transported down the cable between the center conductor and the shield. However, the shields of most practical cables do not provide perfect containment of the internal electromagnetic fields nor isolation from external fields. As shown, a small fraction of the cable's internal field is usually coupled to the external space. External fields are coupled into the cable in a similar manner. The existence of this weak coupling between internal and external fields forms the basis for several guided wireless systems for communicating with roving miners. Cables which transport most of the signal energy inside the cable have an added advantage; namely, performance is essentially not affected by normal accumulations of dirt and moisture, nor by installing the cable directly against the rib of a haulage way.

Figure 11. - Guided Wireless Radio with Coaxial Cable,
Principle of Operation

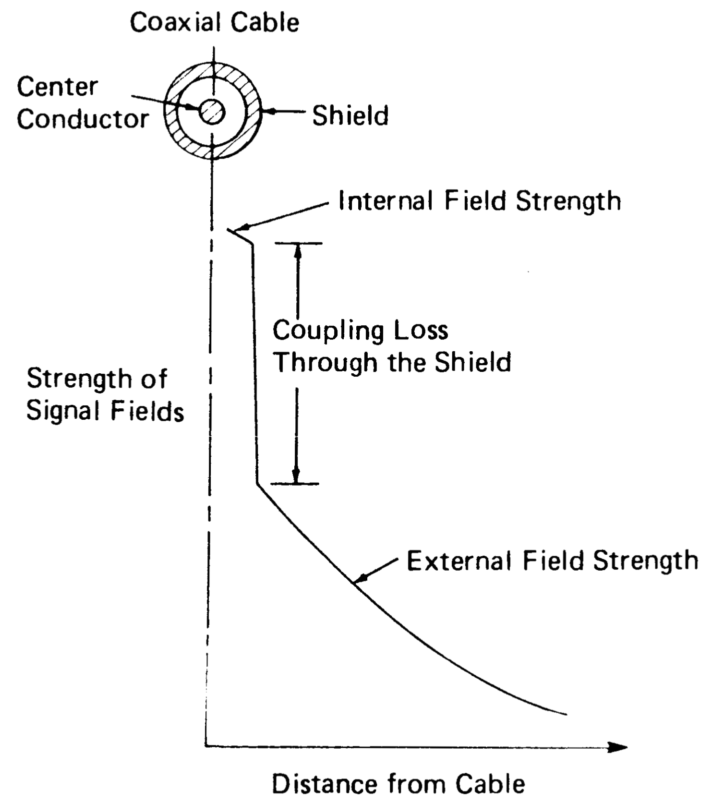


FIGURE 11 GUIDED WIRELESS RADIO WITH COAXIAL CABLE, PRINCIPLE OF OPERATION

As shown in Figure 11, the fields coupled to the external space will continue to decrease in strength with increasing distance from the cable. In addition, the internal and external fields will be attenuated, primarily because of the cable's resistance, as they travel along the cable to and from the fixed and portable communication stations. The amount of coupling loss and longitudinal attenuation loss experienced depends on the material and construction of the cable and on the operating frequency.

The UHF guided wireless system treated in this seminar is one based on the use of special semi-flexible RX4-1 Radiax coaxial cable of 1/2-inch diameter and 50 ohm characteristic impedance. The cable has a solid copper shield in which holes have been machined to increase the amount of coupling to the external space, as opposed to the braided-type shield used in conventional flexible cables for lower frequency applications. A cut-away view of the Radiax cable is shown in Figure 12. Its cost is more than ten times that of conventional braided cable used for cable television home installations. According to the cable manufacturer, Andrew Corporation, a lateral coupling loss of 85 ± 10 dB is experienced when the external signal strength is measured at a distance of 20 feet from RX4-1 Radiax cable. This loss includes the shield coupling loss and the radial spreading loss for this distance and applies for both incoming and outgoing signals. The longitudinal attenuation loss is 2.1 dB/100 feet.

Figure 12. - Radiax Coaxial Cable, Cut-a-Way View

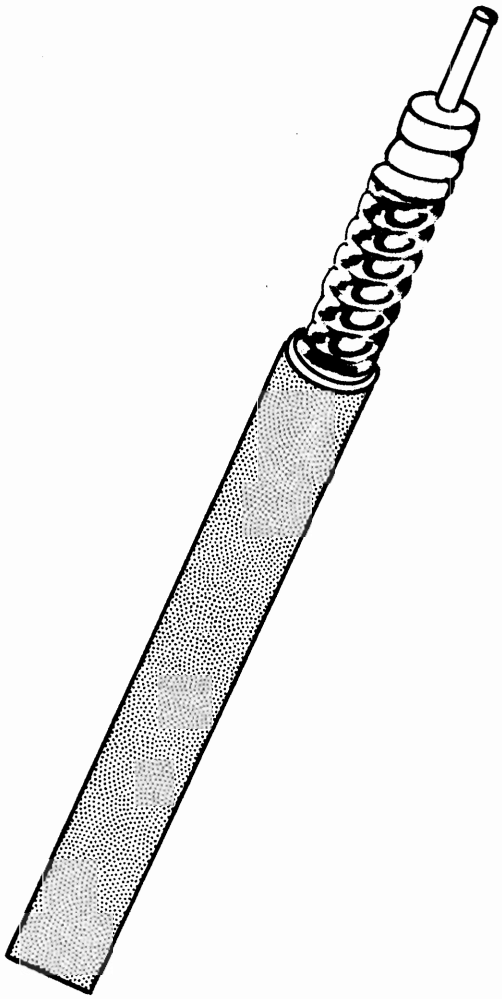

FIGURE 12 RADIAX COAXIAL CABLE, CUT-AWAY VIEW

Figure 13 is a sketch illustrating how signals both in the cable and in the haulage way decrease in strength as the distance along the cable from a repeater station is increased. Signal voltages and external fields are reduced in strength by a factor of 10-1 (20 dB) for every 950 feet of cable traveled, due to the 2.1 dB/100 ft longitudinal attenuation rate. Figure 13 depicts the decrease in signal strength for transmissions by the repeater. A similar signal strength decrease occurs for transmissions from a handy talkie, but with the signal strength now being largest at the handy talkie location and decreasing as the signal travels in the cable towards the repeater.

Figure 13. - Two-Way Communication Range for Radiax Guided Wireless Radio System

In spite of the holes, the coupling loss imposed by the shield is still high and requires the use of repeaters (to amplify and retransmit incoming signals) to allow communication via this cable between roving miners carrying portable handy talkie radios. The spacing of these repeaters along the cable (base stations if only a surface-to-mine channel is desired) will be governed primarily by the lateral range desired from the cable, the longitudinal attenuation rate of the cable, and the transmitter power of the portable units. Since the transmitter power available for portable units is generally lower than that available for fixed repeater or base stations, the portable units set the coverage limits for two-way communications.

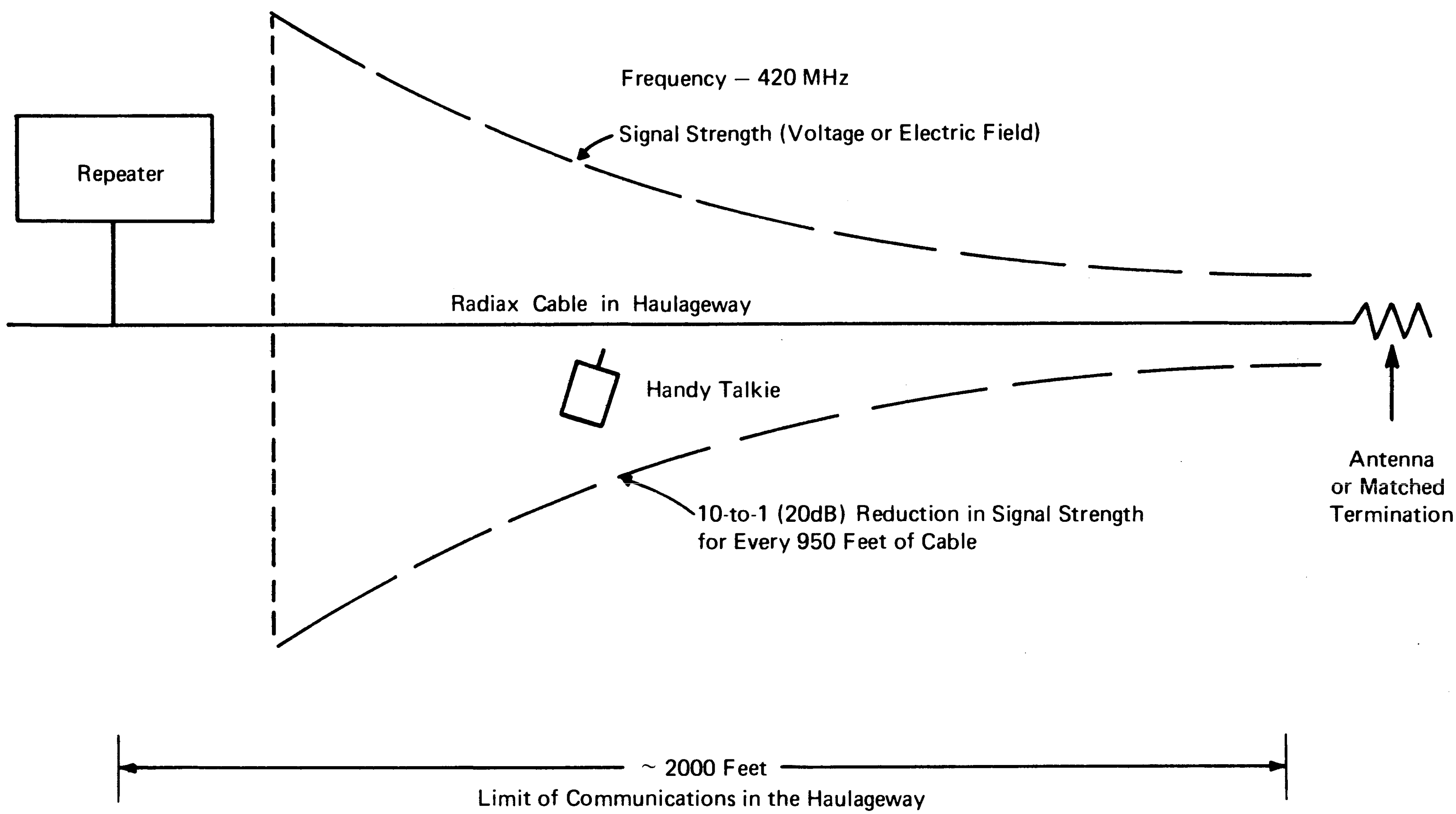


FIGURE 13 TWO-WAY COMMUNICATION RANGE FOR RADIAX GUIDED WIRELESS RADIO SYSTEM

## Expected Coverage

The two-way coverage obtainable with a guided wireless radio system has been estimated for a haulage way installation consisting of the Andrew RX4-1 Radiax coaxial cable, two-watt base stations and repeaters, and the same Motorola HT220 two-watt handy talkies used for the wireless section radio system. As in the case of wireless section radio, communication range will be limited by intrinsic receiver noise as opposed to external electrical noise. The coverage estimates are based on lateral coupling loss and longitudinal attenuation data supplied by the cable manufacturer, preliminary experimental data obtained for the Radiax installation in the Bureau's Safety Research mine, and some of the theoretical and experimental results discussed under wireless section radio. Of particular interest are the ranges expected along haulage ways and down entries crossing haulage ways.

When an entry crossing the haulage way is close to a repeater station, two-way lateral coverage should be possible to handy talkie radios located 300-to-500 feet down the cross entry. Figure 14 illustrates the expected signal behavior and coverage down such a cross entry. Once the UHF signal field becomes well established in the cross entry, its propagation down the entry and around subsequent corners will be governed by the same principles and attenuation rates discussed under wireless section radio.

Figure 14. - Guided Wireless Radio System, Propagation Down Cross-Cuts Off Haulage Ways

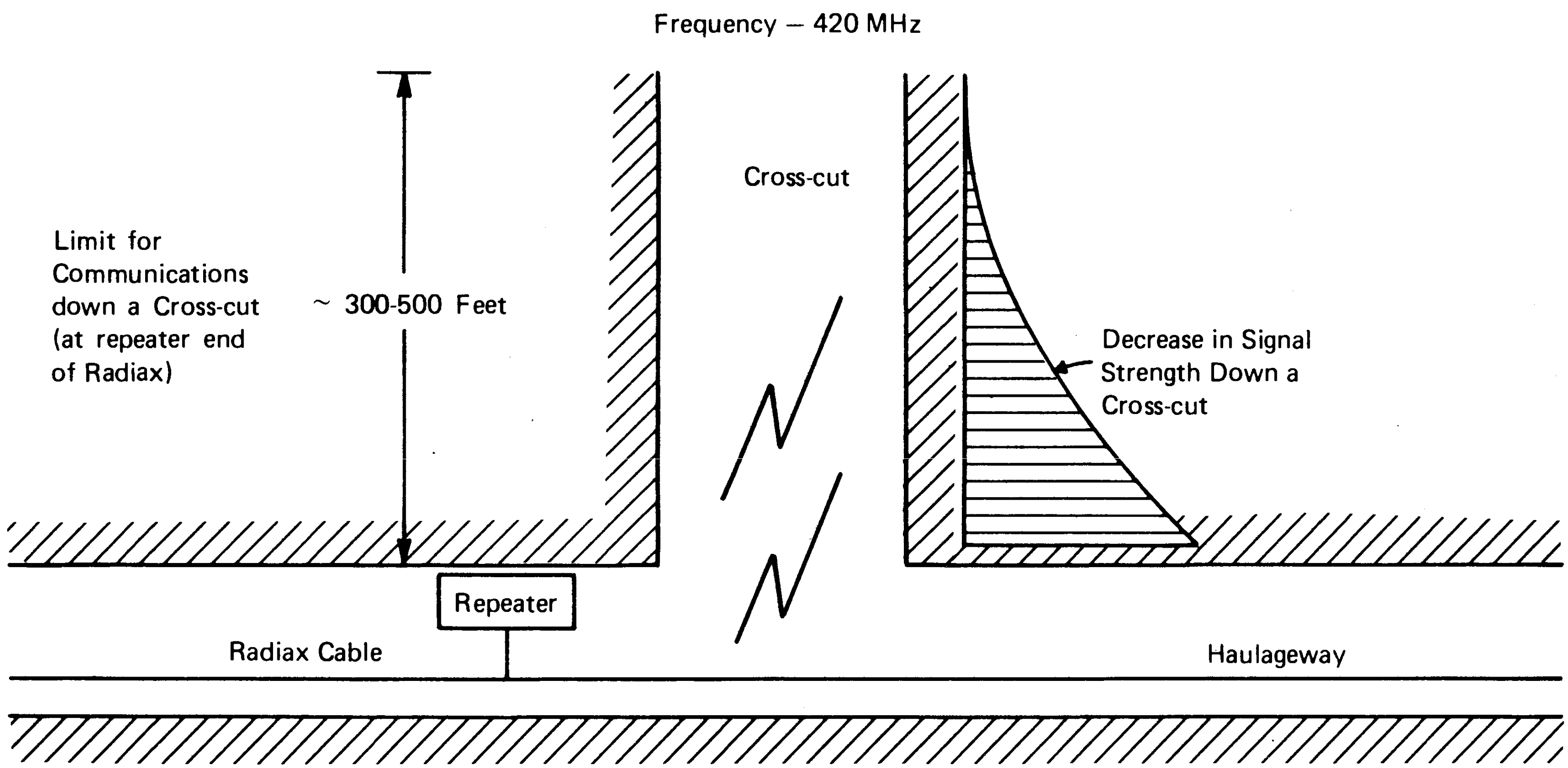


FIGURE 14 GUIDED WIRELESS RADIO SYSTEM, PROPAGATION DOWN CROSS-CUTS OFF HAULAGE WAYS

As the distance between the cross entry and the haulage way repeater station becomes larger, the signal available at the mouth of the entry will become weaker, so the lateral coverage down the cross entry will be correspondingly reduced. Eventually the two-way coverage will be restricted to the confines of the haulage way cross-section. The manufacturers of the cable and portable handy talkies, Andrew and Motorola respectively, have found that coverage becomes confined to the haulage way at a distance of approximately 2,000 feet down the cable from the repeater station as indicated in Figure 13 above. This 2,000-foot distance limit dictates that a UHF Radiax cable system, if designed to give two-way coverage primarily in the haulage way, will require a repeater placed at the center of each 4,000-foot run of cable. If coverage is also desired down cross entries, the spacing between the repeaters will have to be reduced to meet the minimum two-way lateral coverage required in the cross entry located midway between repeater stations.

In sum, the UHF Radiax-based guided wireless system does provide some lateral two-way coverage down entries crossing haulage ways, but this lateral coverage does not remain constant or large over a substantial length of a cable run. This decreases the attractiveness of the Radiax system from the standpoints of cost and practicality for providing area coverage in a U.S. mine environment. If, on the other hand, the coverage requirement can be limited to the haulage way, this requirement can be more economically satisfied in a practical manner by using much lower frequencies together with less expensive coaxial cables, the mine power cables, or the trolley wire/track transmission line.

## System Description

Figure 15 is a block diagram of a basic UHF guided wireless radio system using Radiax cable. It represents the kind of equipment needed for a UHF haulage way application. The system also has a branch-off and associated antenna termination to allow communication with roving miners on a section. Communications from the surface to a roving miner are established by means of audio and control lines that go from the control console on the surface to repeaters (or base stations) at fixed locations in the haulage way. The transmitters of these fixed stations send UHF radio signals down the Radiax cable to roving miners equipped with portable handy talkies. These handy talkies pick up a portion of the signal energy coupled into the haulage way by the holes in the shield of the cable. Conversely, radio transmissions from the roving miners are picked up via the holes in the cable and carried inside the cable to a repeater or base station, where the audio output is sent via the audio and control lines to the control console on the surface.

Figure 15. - A UHF Guided Wireless Radio System Using Radiax Cable

If only roving miner-to-surface communication is required, base stations instead of repeaters can be used, with only a single frequency (channel two) for transmit and receive being required for both the base stations and portable units. If roving miner-to-roving miner communication is required, in addition to communication with the surface, repeater stations that receive, amplify, and retransmit signals from the

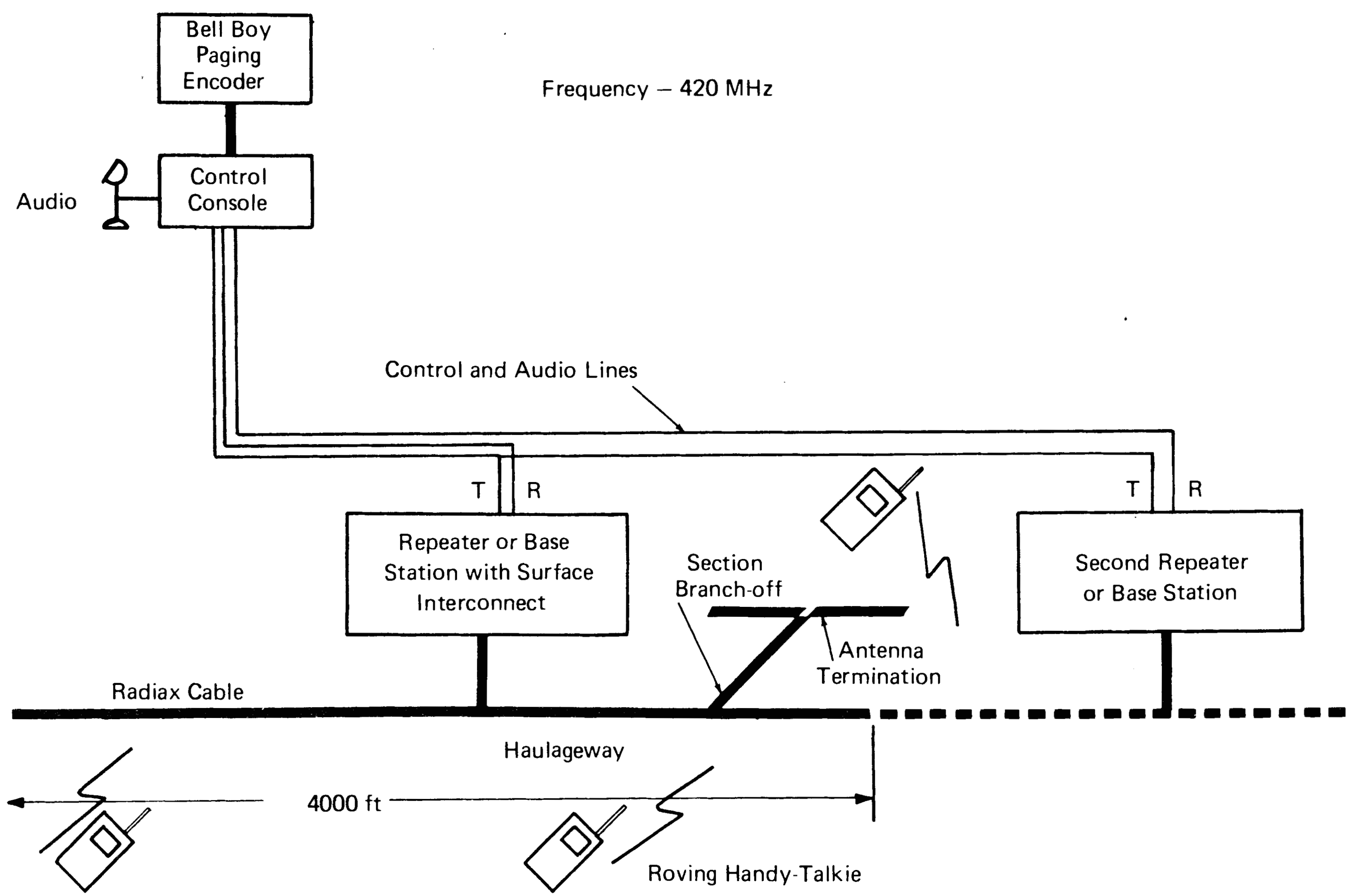


FIGURE 15 A UHF GUIDED WIRELESS RADIO SYSTEM USING RADIAX CABLE

portables must be used, together with two frequencies. (In this case, channels one and two will be needed for transmit and receive by the portables, respectively, and vice versa for the repeater stations.) Adequate two-way coverage in the haulage way is obtained by spacing the repeaters or base stations 4000 feet apart.

As shown in Figure 15, each fixed station has an independent audio line for relaying received messages to the surface. However, a common audio line is used to activate all fixed stations along the haulage way for transmitting messages from the surface. This allows the surface to cover the entire haulage way with a single transmission, and to receive noninterfering replies from miners located along different 4000-foot sections of the cable. To provide roving miner-to-roving miner communication between miners located along different 4000-foot sections of cable, additional audio and control lines must be run between each of the repeater stations, to allow each message from a portable to be automatically retransmitted by all repeater stations along the haulage way.

Figure 16 depicts a UHF guided wireless radio Radiax cable system installed in the Bureau's Safety Research mine. The dimensions of this small mine approach those of a 600 ft. x 600 ft. mine section, so the cable layout is somewhat representative for a section application without an antenna termination. A two frequency 12-watt Motorola repeater station located outside the mine is used for miner-to-miner and miner-to-surface communications. A single frequency 40-watt Motorola base station located in the mine is used as an alternative miner-to-surface communication path. The system is also equipped with a paging encoder as indicated in Figure 15. This encoder provides a more limited call alert or paging mode of operation with less expensive pocket pagers instead of handy talkies.

Figure 16. - UHF 420 MHz Guided Wireless Radio System Installed in the Safety Research Mine

Figure 17 shows the system control console which would normally be located on the surface. Figure 18 is a photograph of the two-frequency 12-watt repeater station, while Figure 19 shows the 40-watt base station and special power supply unit. The 2-watt handy talkies are the same ones discussed under wireless section radio and are shown in Figure 7.

Figure 17. - System Control Console

Figure 18. - Two-Frequency 12-Watt Repeater Station

Figure 19. - Single Frequency 40-Watt Base Station and Special Power Supply Unit

The installation shown in Figure 16 did not meet our performance expectations despite the use of approximately 2,000 feet of Radiax cable. Complete two-way coverage of the mine was not obtained. The worst areas were largely located in the left half of the mine, particularly in the vertical cross-cut with the 45-degree corner on the map in Figure 16, but pockets of weak performance were also present in other parts of the mine. Means of improving this performance by the addition of antenna terminations at selected locations are currently under investigation.

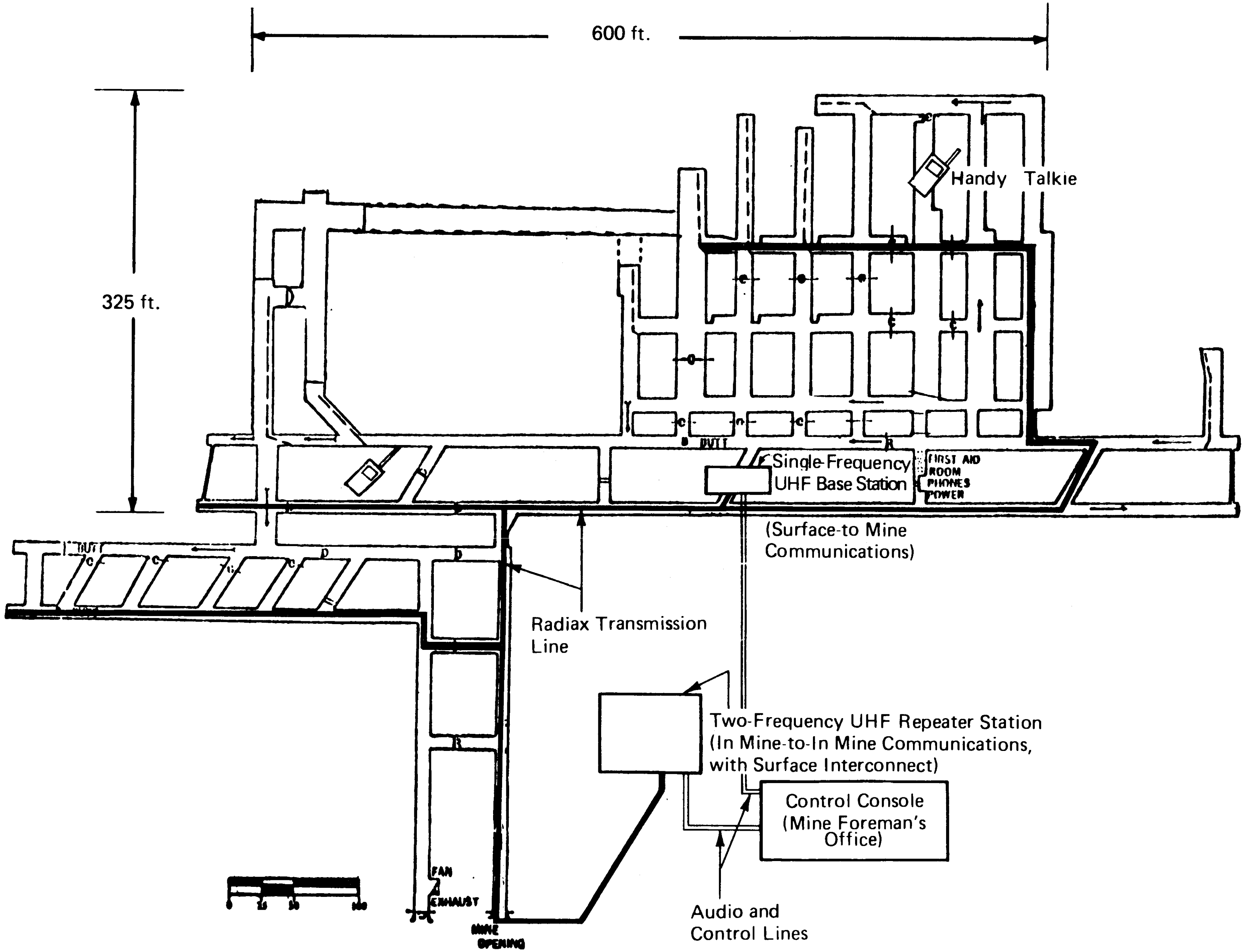


FIGURE 16 UHF 420 MHz GUIDED WIRELESS RADIO SYSTEM INSTALLED IN THE SAFETY RESEARCH MINE

FIGURE 17    SYSTEM CONTROL CONSOLE

FIGURE 18 TWO-FREQUENCY 12-WATT REPEATER STATION

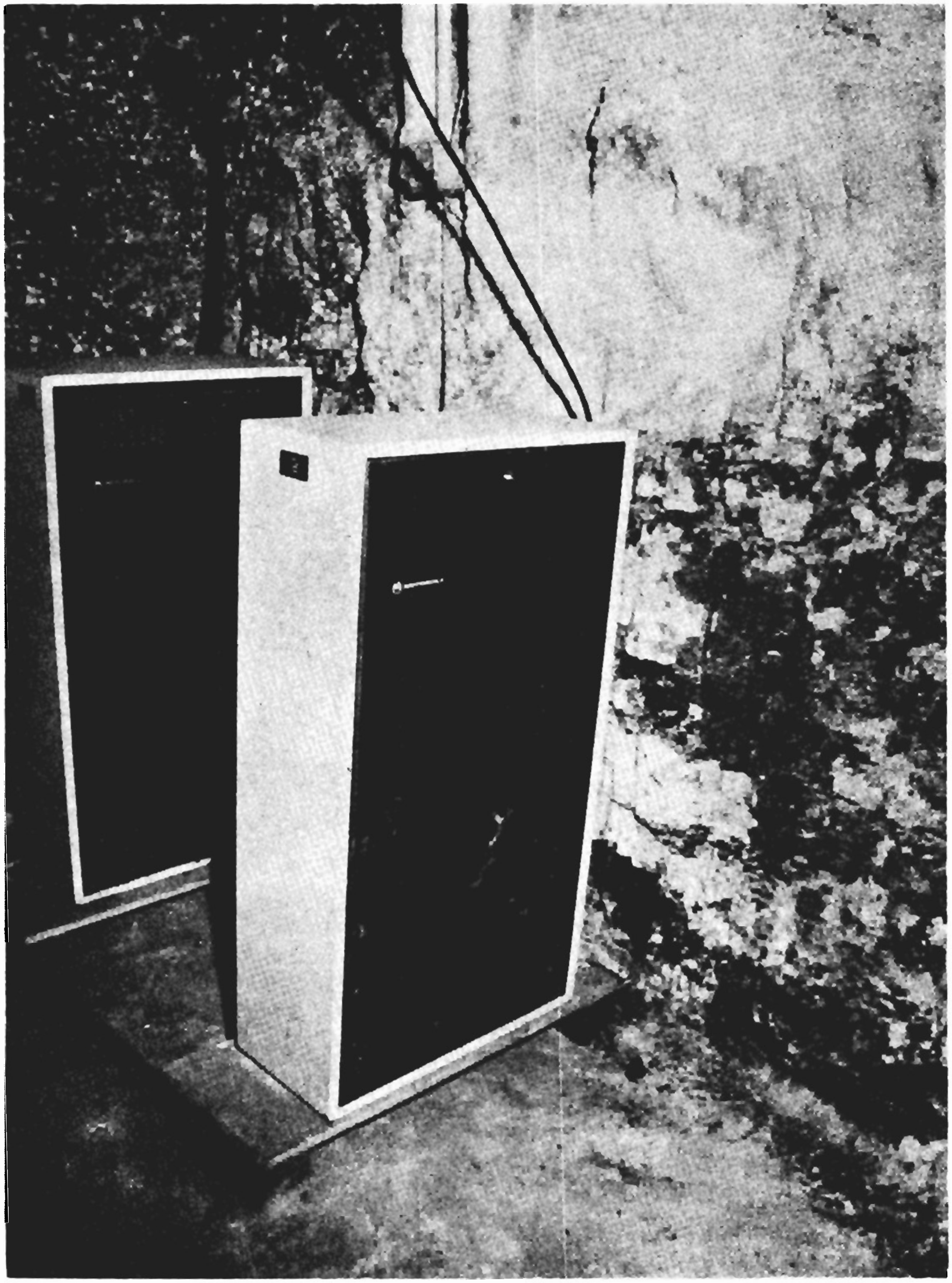

FIGURE 19 SINGLE FREQUENCY 40-WATT BASE STATION AND SPECIAL POWER SUPPLY UNIT

## UHF OVERLAND LOOPBACK

The Bureau has also investigated means of looping underground communication channels back to their points of origin on the surface. An example of a typical overland radio loopback channel is shown as part of Figure 10. In this illustration it is used to loopback a Radiax guided wireless radio communications channel. As shown in Figure 10 the audio output of an in-mine fixed station is brought, via audio and control lines in a power borehole or ventilation shaft, to a surface loopback station consisting of a 12-watt, six-channel UHF transmitter/receiver and associated antenna. Figure 20 is a photograph of such a surface loopback station located near a borehole. The UHF radio loopback system can also loopback the outputs of the underground mine phone and carrier phone communication channels, and those of mine environment monitoring channels. This is done by running independent sets of wires up the same borehole to the UHF loopback station on the surface and occupying more of its UHF channels. On the surface, all messages are transmitted overland to a similar transmit/receive station located near the mine foreman's office, and subsequently to appropriate monitoring or control stations.

Figure 20. - Surface Transmitter/Receiver/Antenna Station for Overland Radio Loopback

By placing the surface stations at strategic locations, the mine phone line, trolley wire, and environment monitoring channels as well as wireless and guided wireless channels can be looped back together. In this manner every transmission that goes into the mine via a primary route can be sent out again via the overland loopback. If a break should occur in any

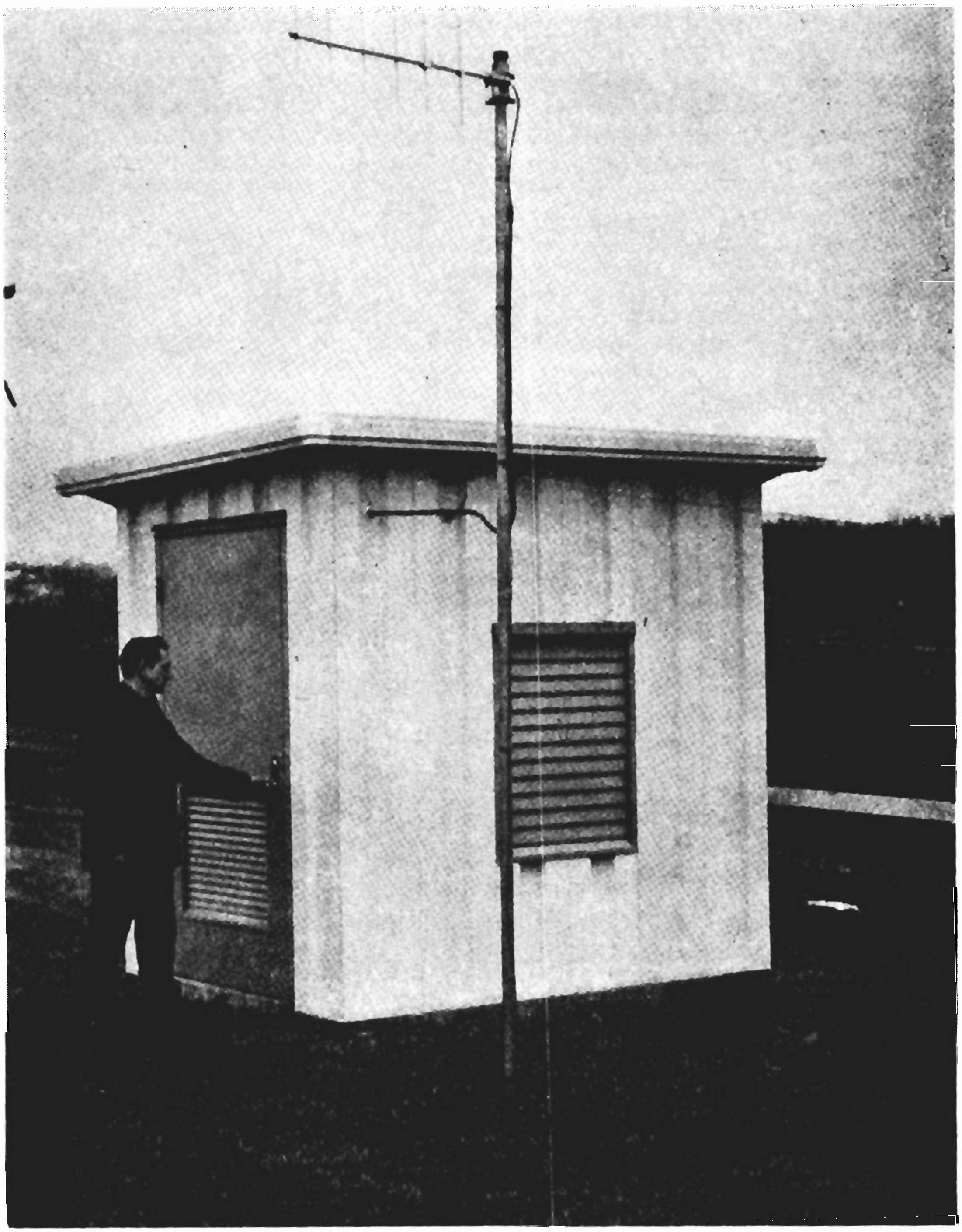

FIGURE 20 SURFACE TRANSMITTER/RECEIVER/ANTENNA STATION FOR OVERLAND RADIO LOOPBACK

one of the communication channels and a miner inby the break cannot be reached by the primary route, the loopback route can be used to reach him. Surface power lines and telephone lines are also suitable for looping back in-mine communication channels.

## CONCLUDING REMARKS

The general features of the methods discussed in this paper for establishing two-way wireless and guided wireless radio communications between underground roving miners at UHF are summarized in Table 1.

Table 1. - UHF Radio In Mines for Roving Miner-to-Miner Communications

| Method | Units of Coverage | Equipment (per unit of coverage) |
|---|---|---|
| Direct Wireless | Half Section, or 0.3 Mile of Haulage Way | Handy Talkies |
| Wireless Via Repeater | Whole Section, or 0.6 Mile of Haulage Way | Handy Talkies, Plus Central Low-Power Repeater |
| Guided Wireless Via Repeater and Radiax Cable | Whole Section, or 0.8 Mile of Haulage Way | Handy Talkies, Plus Central High-Power Standard Repeater, Plus Radiax Cable Along Haulage Way or Distributed in Section |

Furthermore, roving miner communications can be established with the surface, and between separate coverage units along haulage ways or different sections, by adding interconnect equipment appropriate to each method. The wireless-via-repeater method can use a radio-to-carrier interconnect to the existing mine phone line at each repeater location, together with a standard carrier phone at the surface end of the mine phone line. The guided wireless method can use interconnect equipment similar to that for the wireless method, or install a set of audio and control lines connecting all the repeater stations with each other and with a surface console station. The latter approach is the current practice for Radiax-based guided wireless systems.

In sum, our investigations reveal that UHF wireless section radio is more effective, practical and economical than Radiax-based UHF guided wireless radio for both section and haulage way roving miner applications. Wireless section radio also provides superior flexibility for establishing two-way communications at locations that may temporarily require wireless coverage because of an emergency or maintenance problem. For strictly haulage way applications, much lower frequencies and lower cost transmission lines appear to offer other advantages, and are presently being investigated.

## II. THROUGH-THE-EARTH ELECTROMAGNETICS WORKSHOP

### A. INTRODUCTION

During the summer of 1973, ADL provided technical and support assistance to PMSRC related to a Bureau-sponsored Through-the-Earth Electromagnetics Workshop at the Colorado School of Mines. This workshop brought together people currently doing research and development relating to the design of electromagnetic systems for communicating with, and/or locating, subsurface miners. The objective of this workshop was to present and discuss the latest results of the work of these investigators; to summarize the present status of developments related to this work; and to recommend short- and long-term research and development efforts needed to advance the state-of-the-art and further the development of practical electromagnetic mine communication and location systems.

ADL's assistance included: technical planning and supporting services related to the Bureau's participation in the workshop; active participation of ADL staff during the workshop, both in the presentation of a Bureau-sponsored paper entitled, "Theory of the Propagation of UHF Radio Waves in Coal Mine Tunnels", and as Chairmen of two Working Groups on "Uplink and Downlink Communications" and "Operational Communications"; reviewing of papers submitted for the Workshop Proceedings; and preparation of two reports summarizing the present status and recommendations regarding the research and development areas treated by the above Working Groups.

The UHF Theory summary paper and the two Working Group summary reports mentioned above will appear in the Proceedings of the Workshop,* and have been included in the following sections of this Part for convenient reference.

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* These Proceedings are to be published as part of the Colorado School of Mines Final Report to the Bureau of Mines on Grant G133023.

## B. THEORY OF THE PROPAGATION OF UHF RADIO WAVES IN COAL MINE TUNNELS

by

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### ABSTRACT

This paper is concerned with the theoretical study of UHF radio communication in coal mines, with particular reference to the rate of loss of signal strength along a tunnel, and from one tunnel to another around a corner. Of prime interest are the nature of the propagation mechanism and the prediction of the radio frequency that propagates with the smallest loss. Our theoretical results are compared with measurements made by Collins Radio Co. This work was conducted as part of the Pittsburgh Mining and Safety Research Center's investigation of new ways to reach and extend two-way communications to the key individuals that are highly mobile within the sections and haulage ways of coal mines.

### INTRODUCTION

At frequencies in the range of 200-4,000 MHz the rock and coal bounding a coal mine tunnel act as relatively low loss dielectrics with dielectric constants in the range 5-10. Under these conditions a reasonable hypothesis is that transmission takes the form of waveguide propagation in a tunnel, since the wavelengths of the UHF waves are smaller than the tunnel dimensions. An electromagnetic wave traveling along a rectangular tunnel in a dielectric medium can propagate in any one of a number of allowed waveguide modes. All of these modes are "lossy modes" owing to the fact that any part of the wave that impinges on a wall of the tunnel is partially refracted into the surrounding dielectric and partially reflected back into the waveguide. The refracted part propagates away from the waveguide and represents a power loss. This type of waveguide mode differs from the light-pipe modes in glass fibers in which total internal reflection occurs at the wall of the fiber, with zero power loss if the fiber and the matrix in which it is embedded are both lossless. It is to be noted that the attenuation rates of the waveguide modes studied in this paper depend almost entirely on refraction loss, both for the dominant mode and higher modes excited by scattering, rather than on ohmic loss. The effect of ohmic loss due to the small conductivity of the surrounding material is found to be negligible at the frequencies of interest here, and will not be further discussed.

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies of the Interior Department's Bureau of Mines or the U.S. Government. This paper was prepared under USBM Contract No. H0122026.

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2. Arthur D. Little, Inc., Cambridge, Massachusetts.

The study reported here is concerned with tunnels of rectangular cross section and the theory includes the case where the dielectric constant of the material on the side walls of the tunnel is different from that on top and bottom walls. The work extends the earlier theoretical work by Marcatili and Schmeltzer(1) and by Glaser(2) which applies to waveguides of circular and parallel-plate geometry in a medium of uniform dielectric constant.

In this paper we present the main features of the propagation of UHF waves in tunnels. Details of the derivations are contained in Arthur D. Little, Inc. reports.(3)

## THE FUNDAMENTAL (1,1) WAVEGUIDE MODES

The propagation modes with the lowest attenuation rates in a rectangular tunnel in a dielectric medium are the two (1,1) modes which have the electric field $\vec{E}$ polarized predominantly in the horizontal and vertical directions, respectively. We will refer to these two modes as the $E_h$ and $E_v$ modes.

The main field components of the $E_h$ mode in the tunnel are

$$E_x = E_0 \cos k_x x \cos k_y y \, e^{-ik_z z} \tag{1}$$

$$H_y = (k_z/\omega\mu_0)E_0 \cos k_x x \cos k_y y \, e^{-ik_z z} \tag{2}$$

where the symbols have their customary meaning. The coordinate system is centered in the tunnel with x horizontal, y vertical, and z along the tunnel. In addition to these transverse field components there are small longitudinal components $E_z$ and $H_z$ and a small transverse component $H_x$. For the frequencies of interest here $k_x$ and $k_y$ are small compared with $k_z$ which means that the wave propagation is mostly in the z-direction. From a geometrical optics point of view, the ray makes small grazing angles with the tunnel walls.

In the dielectric surrounding the tunnel the wave solution has the form of progressive waves in the transverse as well as the longitudinal directions. The propagation constant $k_z$ for the (1,1) mode is an eigenvalue determined by the boundary conditions of continuity of the tangential components of $\vec{E}$ and $\vec{H}$ at the walls of the tunnel. Owing to the simple form of the wave given by (1) and (2) these conditions can be satisfied only approximately. However, a good approximation to $k_z$ is obtained. The imaginary part of $k_z$, which arises owing to the leaky nature of the mode, gives the attenuation rate of the wave. The loss $L_{Eh}$ in dB for the (1,1) $E_h$ mode is given by

$$L_{Eh} = 4.343 \, \lambda^2 \, z \left( \frac{K_1}{d_1^3 \sqrt{K_1 - 1}} + \frac{1}{d_2^3 \sqrt{K_2 - 1}} \right) \tag{3}$$

where $K_1$ is the dielectric constant of the side walls and $K_2$ of the roof and floor of the tunnel. The corresponding result for the (1,1) $E_v$ mode is

$$L_{E_v} = 4.343\,\lambda^2\,z\left(\frac{1}{d_1^3\sqrt{K_1-1}} + \frac{K_2}{d_2^3\sqrt{K_2-1}}\right) \tag{4}$$

These results are valid if the wavelength $\lambda$ is small compared with the tunnel dimensions $d_1$ and $d_2$. The same formulas are also obtained if one adds the attenuations for horizontal and vertical slot waveguides with dimensions $d_2$ and $d_1$, and dielectric constants $K_2$ and $K_1$, respectively. The losses calculated by (3) and (4) also agree closely with those calculated by a ray approach.

Figure 1 shows loss rates in dB/100 ft as functions of frequency calculated by (3) and (4) for the (1,1) $E_h$ and $E_v$ modes in a tunnel of width 14 ft and height 7 ft, representative of a haulage way in a seam of high coal, and for $K_1 = K_2 = 10$, corresponding to coal on all the walls of the tunnel. It is seen that the loss rate is much greater for the $E_v$ mode. Figure 2 shows the calculated $E_h$ loss rate for a tunnel of half the height. The higher loss rate in the low coal tunnel is due to the effect of the $d_2^3$ term in (3).

Two experimental values obtained by Collins Radio Co.[4] for horizontal-horizontal antenna orientations are also shown in Figure 1. These values agree well with theory for the $E_h$ mode for 415 MHz, but not so well for 1000 MHz. The departure suggests that some additional loss mechanism sets in at higher frequencies.

It is also significant that the experimental values of the loss rates for all three orientation arrangements of the transmitting and receiving dipole antennas, namely, horizontal-horizontal, vertical-horizontal, and vertical-vertical, are surprisingly close to each other. The independence of loss rate with respect to polarization is not predicted by the theory discussed so far, as seen in Figure 1 for the $E_h$ and $E_v$ modes. Indeed, the theory predicts no transmission at all for the VH antenna arrangement.

## PROPAGATION MODEL

The higher observed loss rate at the higher frequencies relative to the calculated $E_h$ mode values, and the independence of the loss rate on antenna orientation can both be accounted for if one allows for scattering of the dominant (1,1) $E_h$ mode by roughness and tilt of the tunnel walls. The scattered radiation goes into many higher modes and can be regarded as a diffuse radiation component that accompanies the $E_h$ mode. The diffuse component is in dynamical equilibrium with the $E_h$ mode in the sense that its rate of generation by scattering of the $E_h$ mode is balanced by its rate of loss by refraction into the surrounding dielectric. Since the diffuse component consists of contributions from the (1,1) $E_v$ mode and many higher order waveguide modes, all of which have much higher refractive loss rates than the fundamental $E_h$ mode, the dynamical balance point is such that the level of the diffuse component is many dB below that of the $E_h$ mode at any point in the tunnel.

Our propagation model, comprising the (1,1) $E_h$ mode plus an equilibrium diffuse component, explains the discrepancy between theory and experiment in Figure 1, since the loss due to scattering of the $E_h$ mode is greater at 1000 MHz than at 415 MHz owing to the larger effect of wall tilt at the higher frequency. The model accounts for the independence of loss rate on antenna orientation, since the loss rate is always that of the $E_h$ mode, except for initial and final transition regions, no matter what the orientations of the two antennas may be. The transition regions, however, cause different insertion losses for the different antenna orientations.

Further strong support for the theoretical model is provided by the discovery by Collins Radio Co. that a large loss in signal strength occurs when the receiving antenna is moved around a corner into a cross tunnel; and that the signal strength around the corner is independent of receiving antenna orientation. This is exactly what our model predicts since the well collimated $E_h$ mode in the main tunnel couples very weakly into the cross tunnel, whereas the uncollimated diffuse component couples quite efficiently. Since the diffuse radiation component is likely to be almost unpolarized, the observed independence of signal strength on receiving antenna orientation is understandable.

Another experimental result is that the initial attenuation rate in the cross tunnel is much higher than the rate in the main tunnel. This is also in accord with the model since the diffuse radiation component has a much larger loss rate than the $E_h$ mode owing to its steeper angles of incidence on the tunnel walls.

## THE DIFFUSE RADIATION COMPONENT

Scattering of the (1,1) $E_h$ mode into other modes to generate the diffuse component occurs by two mechanisms: wall roughness and wall tilt.

Roughness is here regarded as local variations in the level of the surface relative to the mean level of the surface of a wall. For the case of a Gaussian distribution of the surface level, defined by a root mean square roughness h, the loss in dB by the $E_h$ mode is given by the formula

$$L_{roughness} = 4.343\ \pi^2\ h^2\ \lambda(1/d_1^4 + 1/d_2^4)\ z. \tag{5}$$

This is also the gain by the diffuse component due to roughness.

Long range tilt of the tunnel walls relative to the mean planes which define the dimensions $d_1$ and $d_2$ of the tunnel causes radiation in the $E_h$ mode to be deflected away from the directions defined by the phase condition for the mode. One can calculate the average coupling factor of such deflected radiation back into the $E_h$ mode and thereby find the loss rate due to tilt. The result in dB is

$$L_{tilt} = 4.343\ \pi^2\ \theta^2\ z/\lambda \tag{6}$$

where $\theta$ is the root mean square tilt. Eq. (6) also gives the rate at which the diffuse component gains power from the $E_h$ mode as a result of the tilt.

It is noted from (5) and (6) that roughness is most important at low frequencies while tilt is most important at high frequencies.

Figure 3 shows the effect on the (1,1) $E_h$ mode propagation of adding the loss rates due to roughness and tilt to the direct refraction loss given in Figure 1. The curves are calculated for a root mean square roughness of 4 inches and for various assumed values of $\theta$. It is seen that a value $\theta = 1°$ gives good agreement with the experimental values of Collins Radio Co. The effect of tilt is much greater than that of roughness in the frequency range of interest.

Having determined the value of $\theta$, for the assumed value of h, we can now find the intensity ratio of the diffuse component to the $E_h$ mode from the equilibrium balance equation

$$I_{d,\ main} / I_{h,\ main} = L_{hd} / L_d \tag{7}$$

where $L_{hd}$ is the loss rate from the $E_h$ mode into the diffuse component, and $L_d$ is the loss rate of the diffuse component by refraction. To estimate $L_d$ approximately, we take the loss rate to be that of an "average ray" of the diffuse component having direction cosines $(1/\sqrt{3},\ 1/\sqrt{3},\ 1/\sqrt{3})$. Then

$$L_d = 10\,(z/d_1 + z/d_2)\log_{10} 1/R \tag{8}$$

where R, the Fresnel reflectance of the average ray for $K_1 = K_2 = 10$, has the value 0.28. Then for $d_1 = 14$ ft, $d_2 = 7$ ft, z = 100 ft, we find that $L_d = 119$ dB/100 ft. This value has to be corrected for the loss of diffuse radiation into cross tunnels which we assume have the same dimensions as the main tunnel and occur every 75 ft. From relative area considerations we find that this loss is 2 dB/100 ft. The corrected value is therefore

$$L_d = 121 \text{ dB/100 ft.} \tag{9}$$

which is independent of frequency.

The loss rate $L_{hd}$ is shown in Table I as a function of frequency for the 14 ft x 7 ft tunnel. The values are the sum of the roughness and tilt losses calculated by (5) and (6) for h = 4 inches rms and $\theta = 1°$ rms. The diffuse component level relative to the $E_h$ mode, calculated by (7), is given in the fourth column of Table I. The diffuse component is larger at high frequencies owing to the increased scattering of the $E_h$ mode by wall tilt.

## PROPAGATION AROUND A CORNER

From solid angle considerations one finds that the fraction of the diffuse component in the main tunnel that enters the 14 ft x 7 ft aperture of a cross tunnel is 15% or − 8.2 dB. The diffuse level just inside the aperture of the cross tunnel, relative to the $E_h$ mode level in the main tunnel is therefore obtained by subtracting 8.2 dB from the values in column 4 of Table I. The results are shown in column 5 of the table. A dipole antenna with either horizontal or vertical orientation placed at this point responds to one half of the diffuse radiation, and therefore gives a signal that is 3 dB less than the values in column 5 of Table I, relative to a horizontal antenna in the main tunnel.

If a horizontal antenna is moved down the cross tunnel the loss rate is initially 119 dB/100 ft (the value calculated above without correction for tunnels branching from the cross tunnel). Ultimately, however, the loss rate becomes that of the $E_h$ mode excited in the cross tunnel by the diffuse radiation in the main tunnel. We determine the $E_h$ level at the beginning of the cross tunnel by calculating the fraction of the diffuse radiation leaving the exit aperture of the main tunnel which lies within the solid angle of acceptance of the $E_h$ mode in the cross tunnel. The result is

$$I_{h,\,cross}/I_{d,\,main} = \lambda^3/16\,\pi\,d_1^2\,d_2 \qquad (10)$$

This ratio, in dB, is given in column 2 of Table II.

Column 3 of Table II is the $E_h$ level at the beginning of the cross tunnel relative to the $E_h$ level in the main tunnel found by adding column 2 of Table II and column 4 of Table I. We find the corresponding ratio at 100 ft down the cross tunnel by adding the $E_h$ propagation loss rates given in Figure 3 for $\theta = 1°$. The results are shown in the last column of Table II.

The foregoing theoretical results for the diffuse and $E_h$ components in the cross tunnel allow us to plot straight lines showing the initial and final trends in signal level in the cross tunnel. These asymptotic lines are shown in Figures 4 and 5 for 415 MHz and 1000 MHz, in comparison with the cross tunnel measurements of Collins Radio Co. The agreement both in absolute level and distance dependence gives good support to the theoretical model.

## EFFECT OF ANTENNA ORIENTATION

The theoretical model also allows us to predict the effect of antenna orientation when the transmitting and receiving antennas are far enough apart so that dynamical equilibrium between the $E_h$ mode and the diffuse component is established. We start with both antennas horizontal (HH configuration) and consider this as the 0 dB reference. Then if the receiving antenna is rotated to the vertical (HV configuration) this antenna is now orthogonal to the $E_h$ mode, and therefore responds only to one half of the diffuse component, so that the loss is 3 dB more than the values in Table I, column 4. The result is shown in Table III column 2. Now, by the principle of reciprocity, the transmission for VH is the same as for HV as shown in column 3 of Table III. We now rotate the receiving antenna to get the configuration VV. Again we incur an additional transmission loss of 3 dB more than the values in Table I, column 4. The VV values are shown in Table III, column 4.

## ANTENNA INSERTION LOSS

Dipole or whip antennas are the most convenient for portable radio communications between individuals. However, a considerable loss of signal power occurs at both the transmitter and receiver when simple dipole antennas are used because of the inefficient coupling of these antennas to the waveguide mode. The insertion loss of each dipole antenna can be calculated by a standard microwave circuit technique for computing the amount of power coupled into a waveguide mode by a probe, whereby the dipole antenna is represented as a surface current filament having a sinusoidal current distribution along its length. The result is

$$C = \lambda^2 Z_0/\pi^2 \, d_1 \; d_2 \; R_r. \tag{11}$$

$Z_0$ is the characteristic impedance of the $E_h$ (1,1) mode and $R_r$ is the radiation resistance of the antenna, which are approximately 377 and 73 ohms, respectively, provided that $\lambda$ is small compared with $d_1$ and $d_2$.

Formula (11) applies to antennas placed at the center of the tunnel and gives the results shown in Table IV, where the insertion loss $L_i$ in dB is equal to $-\,10 \log_{10} C$. It is seen that the insertion loss decreases rapidly with increasing wavelength, as one would expect, since the antenna size occupies a larger fraction of the width of the waveguide. The overall insertion loss, for both antennas, is twice the value given in the table. A considerable reduction in loss would result if high gain antenna systems were used.

## OVERALL LOSS IN A STRAIGHT TUNNEL

The overall loss in signal strength in a straight tunnel is the sum of the propagation loss and the insertion losses of the transmitting and receiving antennas. Table V lists the component loss rates for the (1,1) $E_h$ mode due to direct refraction, roughness, and tilt; the total propagation loss rate; the insertion loss for two half-wave antennas; and the overall loss for five different distances. The overall loss for the HH orientation is also shown in Figure 6, where it is seen that the optimum frequency for minimum overall loss is in the range 500-1000 MHz, depending on the desired communication distance.

It is also of interest to combine the results in Table V with those in Table III to obtain the overall loss versus distance for the HH, HV (or VH), and VV antenna orientations. In order to compare the theoretical values with the experimental data of Collins Radio Co., which are expressed with reference to isotropic antennas, we add 4.3 dB to the overall loss calculated for half-wave dipoles. The theoretical results for the three different antenna orientations for frequencies of 415 MHz and 1,000 MHz are compared with the experimental data in Figures 7 and 8. It is seen that the theory agrees quite well with the general trend of the data.

## OVERALL LOSS ALONG A PATH WITH ONE CORNER

Table VI gives the overall $E_h$ mode loss for a path from one tunnel to another, including the corner loss involved in re-establishing the $E_h$ mode in the second tunnel. The loss is the sum of the corner loss, given in column 3 of Table II and repeated in Table VI, and the straight tunnel loss given in Table V for various total distances. The results in Table VI are for the case of half-wave dipole transmitting and receiving antennas and are valid when neither antenna is within about 100 ft of the corner. The overall loss is less than the values in Table VI if the receiving antenna is within this distance, owing to the presence of the rapidly attenuating diffuse component that passes around the corner. From the principle of reciprocity, the same is true if the transmitting antenna is within 100 ft of the corner.

The results indicate that the optimum frequency lies in the range 400-1,000 MHz. However, if one installs horizontal half-wave resonant scattering dipoles with 45° azimuth in the important tunnel intersections, in order to guide the $E_h$ mode around the corner, the optimum may shift to somewhat lower frequencies since a greater fraction of the incident $E_h$ wave will be deflected by the longer low-frequency dipoles.

## CONCLUSIONS

The kind of propagation model developed in this paper, involving the (1,1) $E_h$ waveguide mode accompanied by a diffuse component in dynamical equilibrium with it, seems to be necessary to account for the many effects observed in the measurements of Collins Radio Company: the exponential decay of the wave; the marked polarization effects in a straight tunnel; the independence of decay rate on antenna orientation; the absence of polarization at the beginning of a cross tunnel; the two-slope decay characteristic in a cross tunnel; and overall frequency dependence. All of these effects are moderately well accounted for by the theoretical model. However, considerable refinement of the theory could be made by removing some of the present oversimplifications, such as: the assumption of perfectly diffuse scattering both in the main tunnel and immediately around a corner in a cross tunnel; the use of the "average ray" approximation; and the description of the propagation around a corner in terms of two asymptotes only.

The last item particularly deserves more attention since we have not included the conversion of the diffuse component in the transition region near the beginning of the cross tunnel into the $E_h$ mode. For this reason we think that the good fit of the theory to the experimental data in Figures 4 and 5 may be somewhat fortuitous. More data at greater distances down a cross tunnel would be very desirable to settle this question. Data covering a wider frequency range in both main and cross tunnels would also allow a more stringent test of the theory.

## REFERENCES


1. E. A. J. Marcatili and R. A. Schmeltzer, "Hollow Metallic and Dielectric Waveguides for Long Distance Optical Transmission and Lasers," The Bell System Technical Journal, Vol. 43, 1783, 1964.

2. J. I. Glaser, "Attenuation and Guidance of Modes in Hollow Dielectric Waveguides," IEEE Transactions on Microwave Theory and Techniques, March 1969, p. 173; and M.I.T. Ph.D. Thesis, "Low-Loss Waves in Hollow Dielectric Tubes," February 1967.

3. Arthur D. Little, Inc., reports to U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pa.

4. Collins Radio Company, "Coal Mine Communications Field Test Report," December 29, 1972 prepared for U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pa.

FIGURE 1
REFRACTION LOSS FOR $E_h$ AND $E_v$ MODES IN HIGH COAL

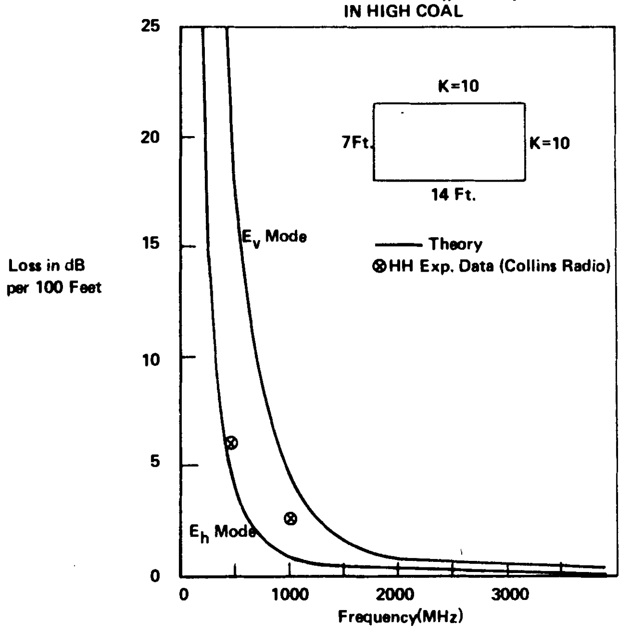


FIGURE 3
RESULTANT PROPAGATION LOSS FOR $E_h$ MODE IN HIGH COAL
(Refraction, Wall Roughness and Tilt)

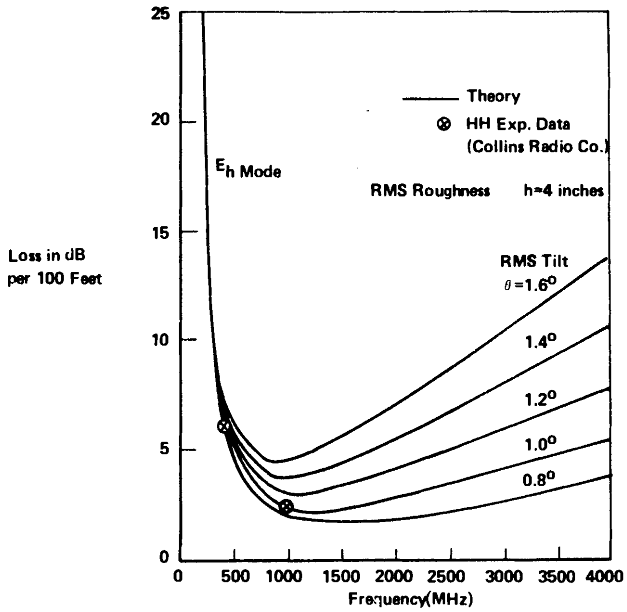


FIGURE 2
REFRACTION LOSS FOR $E_h$ MODE IN LOW COAL

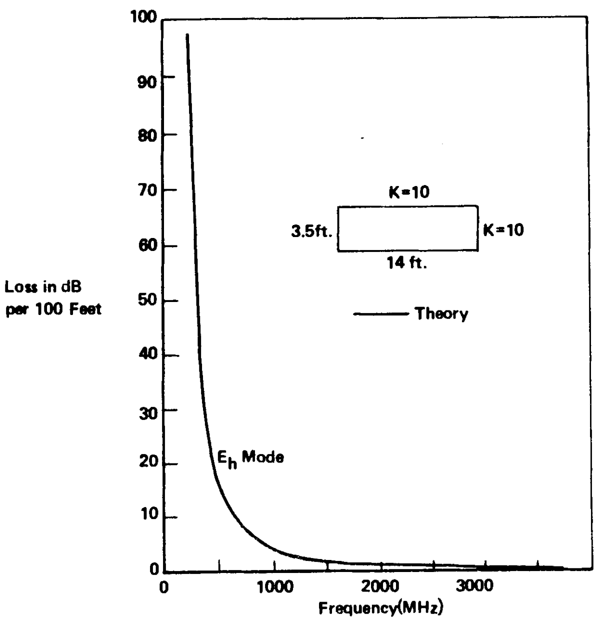


FIGURE 4
CORNER LOSS IN HIGH COAL

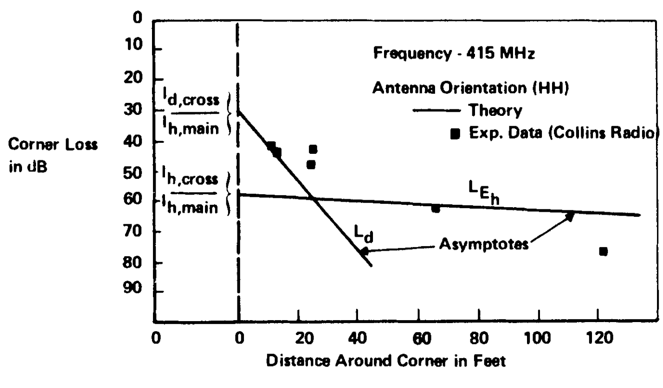

FIGURE 5

CORNER LOSS IN HIGH COAL

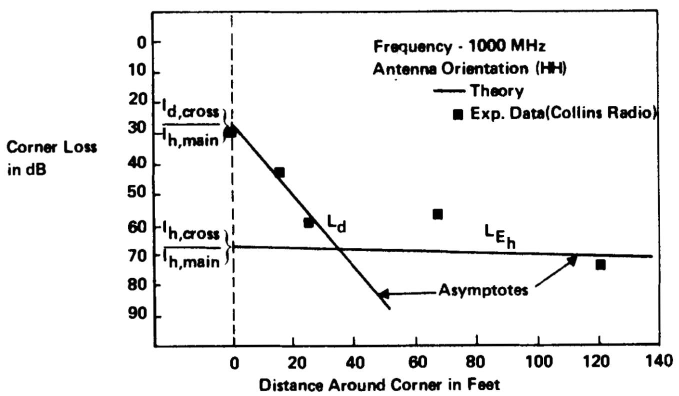


FIGURE 7

OVERALL LOSS IN A STRAIGHT TUNNEL IN HIGH COAL
(For Isotropic Antennas)

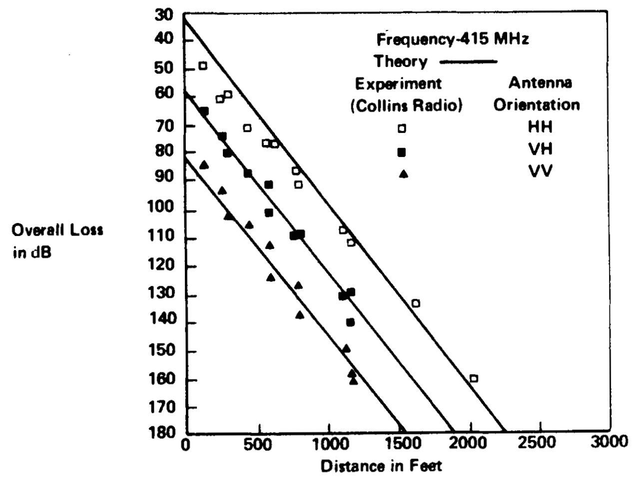


FIGURE 6

TOTAL LOSS FOR VARIOUS DISTANCES ALONG A STRAIGHT TUNNEL

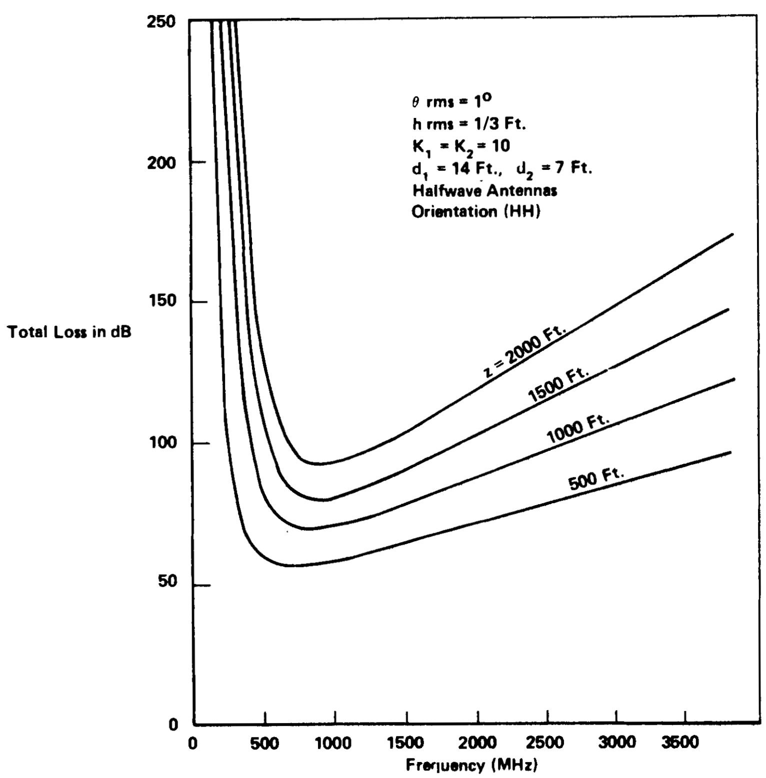


FIGURE 8

OVERALL LOSS IN A STRAIGHT TUNNEL IN HIGH COAL
(For Isotropic Antennas)

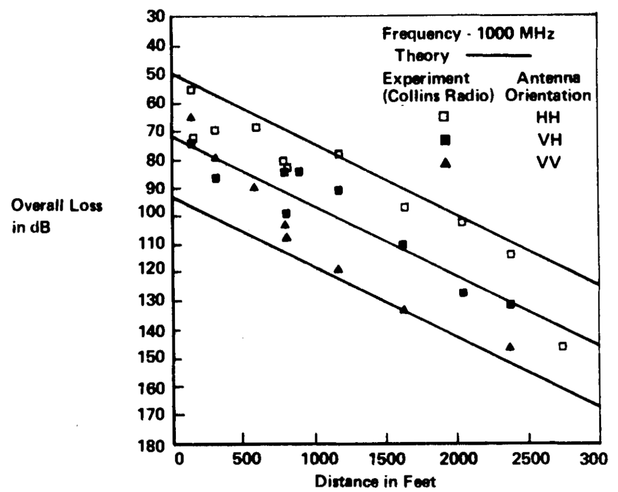

TABLE I

DIFFUSE RADIATION COMPONENT IN MAIN TUNNEL AND AT BEGINNING OF CROSS TUNNEL

| f (MHz) | λ (Ft.) | $L_{hd}$ (dB/100 ft.) | $\frac{I_{d,\,main}}{I_{h,\,main}}$ (dB) | $\frac{I_{d,\,cross}}{I_{h,\,main}}$ (dB) |
|---|---|---|---|---|
| 4,000 | .245 | 5.4 | -13.5 | -21.7 |
| 3,000 | .327 | 4.1 | -14.7 | -22.9 |
| 2,000 | .49 | 2.8 | -16.4 | -24.6 |
| 1,000 | .98 | 1.5 | -19.0 | -27.2 |
| 415 | 2.37 | 1.1 | -20.6 | -28.8 |
| 200 | 4.92 | 1.3 | -19.7 | -27.9 |

TABLE IV
INSERTION LOSS ($L_i$)
(For a Half-Wave Antenna)

| F (MHz) | λ (Feet) | $L_i$ (dB) |
|---|---|---|
| 4000 | 0.245 | 35.0 |
| 3000 | 0.327 | 32.4 |
| 2000 | 0.49 | 28.9 |
| 1000 | 0.98 | 22.9 |
| 415 | 2.37 | 15.2 |
| 200 | 4.92 | 8.9 |

TABLE II

EXCITATION OF $E_h$ MODE IN CROSS TUNNEL BY DIFFUSE COMPONENT IN MAIN TUNNEL

| f (MHz) | $\frac{I_{h,\,cross}}{I_{d,\,main}}$ (dB) | $\left(\frac{I_{h,\,cross}}{I_{h,\,main}}\right)_0$ (dB) | $\left(\frac{I_{h,\,cross}}{I_{h,\,main}}\right)_{100'}$ (dB) |
|---|---|---|---|
| 4,000 | -66.7 | -80.2 | 85.6 |
| 3,000 | -62.9 | -77.6 | 81.8 |
| 2,000 | -57.7 | -74.1 | 77.1 |
| 1,000 | -48.6 | -67.6 | 70.1 |
| 415 | -37.1 | -57.7 | 64.1 |
| 200 | -27.6 | -47.3 | 71.6 |

TABLE V

CALCULATION OF OVERALL LOSS FOR $E_h$ MODE WITH TWO HALFWAVE DIPOLE ANTENNAS

(h = 1/3 Ft. $\theta = 1^o$, $K_1 = K_2 = 10$, $d_1$ = 14 Ft., $d_2$ = 7 Ft.)

| f (MHz) | $L_{refraction}$ (dB/100') | $L_{roughness}$ (dB/100') | $L_{tilt}$ (dB/100') | $L_{propagation}$ (dB/100') | $L_{insertion}$ (dB) | $L_{overall}$ (dB) 100' | 500' | 1000' | 1500' | 2000' |
|---|---|---|---|---|---|---|---|---|---|---|
| 4000 | .06 | .05 | 5.33 | 5.44 | 69.90 | 75 | 97 | 124 | 152 | 179 |
| 3000 | .10 | .07 | 3.99 | 4.16 | 64.88 | 69 | 86 | 107 | 127 | 148 |
| 2000 | .23 | .10 | 2.66 | 2.99 | 57.86 | 61 | 73 | 88 | 103 | 118 |
| 1000 | .91 | .21 | 1.33 | 2.45 | 45.82 | 48 | 58 | 70 | 81 | 93 |
| 415 | 5.34 | .50 | 0.55 | 6.39 | 30.48 | 37 | 62 | 94 | 126 | 158 |
| 200 | 23.00 | 1.04 | 0.27 | 24.31 | 17.80 | 42 | 139 | 261 | 383 | 504 |
| 100 | 92.00 | 2.08 | 0.14 | 94.20 | 5.80 | 100 | 477 | 948 | 1419 | 1890 |

TABLE III
EFFECT OF ANTENNA ORIENTATION

| f (MHz) | HH (dB) | HV (dB) | VH (dB) | VV (dB) |
|---|---|---|---|---|
| 1000 | 0 | -22.0 | -22.0 | -44.0 |
| 415 | 0 | -23.6 | -23.6 | -47.2 |
| 200 | 0 | -22.7 | -22.7 | -45.4 |

TABLE VI

OVERALL LOSS ALONG A PATH INCLUDING ONE CORNER
$E_h$ MODE WITH HALFWAVE DIPOLE ANTENNAS

| f (MHz) | $E_h$ Loss per Corner (dB) | Overall Loss (dB) 500' | 1000' | 1500' | 2000' |
|---|---|---|---|---|---|
| 4000 | 80.2 | 177 | 205 | 232 | 259 |
| 3000 | 77.6 | 163 | 184 | 205 | 226 |
| 2000 | 74.1 | 147 | 162 | 177 | 192 |
| 1000 | 67.6 | 126 | 138 | 148 | 161 |
| 415 | 57.7 | 120 | 152 | 184 | 216 |
| 200 | 47.3 | 187 | 308 | 430 | 551 |

# C. SUMMARY REPORT OF UPLINK AND DOWNLINK COMMUNICATIONS WORKING GROUP

THROUGH-THE-EARTH ELECTROMAGNETICS WORKSHOP

Golden, Colorado

August, 1973

GROUP CHAIRMAN

ROBERT L. LAGACE
ARTHUR D. LITTLE, INC.

# OUTLINE

## OVERVIEW

The attention of this group was focussed on four through-the-earth communication systems that are presently of high interest to the U.S. Bureau of Mines; four systems for providing operational/emergency communications on the working sections of coal mines, indeed up to the very face of the section. The systems are: uplink-data, downlink-voice, sidelink-call alert coded page, sidelink-roof bolt voice page. Each of these systems makes use of the mine overburden as the signal transmission medium, as opposed to the guiding wires, cables, and tunnels treated by the operational communications working group. Each of these systems satisfies one or more of the Bureau's objectives for mine communications systems; namely

- reliable links for monitoring the mine environment under both operational and emergency conditions.
- reliable links for communicating with miners during emergencies.
- special links for increasing the efficiency of day-to-day operations of the mine.

Each of these systems has been successfully demonstrated on a limited experimental basis, and prototypes of all these systems are installed and operating in the USBM experimental mine in Bruceton, Pa. Each of these systems must now be optimized regarding its performance, and engineered for practical routine application to the working sections of actual operating coal mines, particularly those of the room and pillar type.

This optimization and engineering must take place subject to the principal constraints listed by Howard E. Parkinson in his Workshop paper entitled, "Objectives and Constraints of Through-the-Earth Electromagnetic Communications Systems" and enumerated below.

- Depth of Mine Overburden
- Overburden Conductivity
- Electromagnetic Noise In and Above Mines
- Limited In-Mine Electrical Energy (Stationary or Man Carried) During an Emergency
- Intrinsic Safety for In-Mine Equipment
- Practical and Rugged Equipment for Use Under Both Operational/ Emergency Conditions
- Severe Weight Limitations for Man Carried Equipment
- Reasonably Low Costs Especially for Man Carried Equipment

Part II of this paper provides a brief description of each system, while Part III summarizes the present status of developments related to these systems and some recommendations for future work needed to advance these systems to the practical application stage.

## BRIEF DESCRIPTION OF THE FOUR PROMISING SYSTEMS

### Uplink-Data

This is a vertical through-the-earth narrow band data channel for monitoring important parameters of the mine environment under operational and emergency conditions, and for receiving coded messages or replies from miners during an emergency. Operating ranges compatible with 1,000 foot deep mines with $\sigma = 10^{-2}$ mho/m overburden are required. The in-mine transmitter would be located at a key place on the section, such as the loading point, where the present mine pager phone is also terminated. The surface receiver would have to be located in the vicinity of the point directly above the in-mine transmitter, primarily because of the inherent power limitations imposed on an in-mine transmitter during an emergency. This location requirement for the surface receiver may pose a difficulty for some mines with regard to surface access rights over advancing sections, and therefore may restrain such uplink communications to emergency situations during which mobile equipment can be temporarily installed over the known location of the in-mine transmitter. During normal mine operations, the mine environmental data could be monitored by means of a carrier channel over the mine pager phone line.

The limited in-mine transmitter power available during an emergency and the electromagnetic noise levels present on the surface have led to the conclusion that uplink transmission of baseband voice is not a practical goal. Therefore it has been deleted as a requirement until practical, voice bandwidth compression techniques or other types of signal processing become available to change this conclusion.

### Downlink-Voice

This is a vertical through-the-earth voice channel for transmitting messages, during a mine emergency, to miners carrying a small emergency voice receiver, preferably built into their helmets. As in the case of the uplink receiver, difficulties regarding surface access rights over advancing sections may require a mobile surface transmitter installation that is temporarily installed only during emergencies. However, since the transmitter power available on the surface is much greater than that underground during an emergency, the downlink allows greater operational flexibility in communicating with moving miners, and may reduce the surface access rights problem somewhat, because of the potentially greater coverage area of each surface transmitter. As in the uplink case, operating ranges compatible with 1,000 foot deep mines with $\sigma = 10^{-2}$ mho/m overburden are required.

### Sidelink-Call Alert Coded Page

This is a horizontal through-the-earth narrow band channel for transmitting a call alert paging signal to key individuals roving on a working section during normal mine operations, to notify them that they are wanted on the mine pager phone. The transmitter, activated by a signal sent over the mine phone line, would be somewhat centrally located near the section loading point as in the uplink system, and conceivably could be integrated with the uplink equipment if desired. The receivers would be carried by the miner, preferably in his helmot as in the case of the emergency voice receiver for the downlink system. In fact the Bureau's present desire is to have this emergency voice receiver serve a dual role, for key supervisory and maintenance people, by also operating as a narrowband call alert receiver under normal operating conditions. Such a call alert system would extend mine phone paging to roving individuals right up to the working face, thereby increasing both safety and operational efficiency. This would require operating ranges on the order of 400 to 800 feet in overburdens of $\sigma = 10^{-2}$ mho/m in order to cover a typical 600 by 600 foot section, depending on the location of the transmitter.

### Sidelink-Roof Bolt Voice Page

This is a horizontal through-the-earth voice channel for transmitting a more comprehensive voice message or page, as opposed to a simple call alert, to key individuals roving on a working section during normal operating conditions. As in the call alert system the transmitter could also be located at the section loading point, thereby requiring the same operating range as the call alert system. However it most likely would not share equipment with an uplink system as a call alert system might. Being a voice bandwidth system for use under operational conditions when electromagnetic noise levels are high, particularly in the audio band, a significantly higher operating frequency than that possible for a narrowband call alert or uplink system is favored. The receiver for the roof bolt paging system is presently conceived as a pocket-sized unit, but other packages such as a helmet mounted unit are not excluded.

## PRESENT STATUS AND RECOMMENDED FUTURE WORK

To arrive at a design that is at least acceptable, if not optimum, regarding performance and practicality for any of the above communication systems, one usually must first determine how each of the major elements comprising the system influence its performance, and then use them so as to get the desired results. An often indispensible aid to this process, particularly when design information for one or more of the major system elements is missing, is to put together a breadboard system based on existing related hardware and try it out. Several of the above through-the-earth systems have evolved, with beneficial results, from the latter approach. Concurrently, some of the previously missing design information on transmission loss and noise has been accumulated. Therefore, it will now be possible to better optimize each of these systems by quantitative analysis and comparison of alternative designs.

No papers evaluating or describing any of the above through-the-earth systems were presented during the Workshop. However, several papers treating two major system elements, channel transmission loss and noise, were given. These and some past work by the attendees of this working group provided the basis for the group's findings and recommendations. We grouped the system elements as follows:

- The Source: its message, modulation or coding, transmitter, and operating frequency.

- The Channel: its transmission loss for each antenna type, and its noise characteristics.

- The Receiver: its pick up sensor, demodulation/decoding, and special processing for signal to noise improvement.

These elements were then discussed in the context of each of the four systems to the level of detail that was possible under the circumstances. The order of treatment for each system will be Channel, Source, and Receiver, which mainly reflects the emphasis of this Workshop's charter and papers. Progress made to date in the Channel area should now allow more emphasis to be placed on overall system design and analysis, thereby calling greater attention to the Source and Receiver areas.

In the discussions below, that for the uplink system is somewhat longer than the others, because certain elements that have common application to several of the systems are first introduced in the uplink treatment.

Uplink Data System

This section treats the principal narrowband data uplink application. The more difficult, less practical uplink voice application is treated briefly in the downlink voice section.

1. Overview

To date the combination of overburden transmission loss and available surface noise data have identified the frequency band below 5 kHz as the most favorable for practical narrow band uplink data systems intended for coal mines with overburden depths of up to 1,000 feet and conductivity of $\sigma = 10^{-2}$ mho/m. Though shallower mines allow a somewhat higher frequency limit, and more conductive ($\sigma = 10^{-1}$ mho/m) or deeper mine overburdens demand a significantly lower frequency limit, the under 5 kHz limit should cover most coal mine situations.

a. Nominal Mines

Signal to noise analyses performed by Westinghouse Georesearch Laboratory (WGL) support this under 5 kHz conclusion for $10^{-2}$ mho/m overburdens, while also identifying the frequency band between 500 Hz-to-3 kHz as a distinctly optimum one for narrowband systems. The WGL analyses were based on Wait/WGL transmission loss curves for loop transmitters and broadband atmospheric noise data (under 10 kHz) taken by WGL in Colorado. Signal to noise analyses performed by Arthur D. Little, Inc. (ADL) reach a similar under 5 kHz overall conclusion, but do not reveal the presence of an optimum frequency band as distinct as the one by WGL. The ADL analyses were based on the same transmission loss curves of Wait/WGL, but different broadband noise data, namely surface atmospheric noise data (under 300 Hz) taken by MIT Lincoln Laboratory (LL) in Florida and early WGL and National Bureau of Standards (NBS) surface noise data (under 10 kHz) taken over four Western coal mines. The differences in the results of the two analyses, regarding the presence or absence of a clearly optimum frequency band between 500-3000 Hz for $\sigma = 10^{-2}$ mho/m overburdens (based on broadband noise levels) should be easily resolved when the large amount of noise data recently taken over coal mines by NBS soon becomes available. However, WGL and NBS field experiences have revealed a potentially more serious noise problem that may tend to favor use of frequencies between 1-5 kHz over coal mines, namely the extremely strong harmonics of 60 Hz and 360 Hz caused by the mine power conversion equipment, harmonic levels that are high enough in some cases to interfere with even narrowband systems operating between the harmonics.

b. Deep Mines

For mines with overburdens deeper than 1,000 feet (such as hardrock mines) or conductivities greater than $10^{-2}$ mho/m, it is generally agreed that operating frequencies will definitely be forced downward to perhaps 500 Hz or 100 Hz. In some extremely deep hardrock mines that approach 10,000 feet, lower frequencies yet may be needed if direct transmission to the surface is required. The favorable downlink signal transmission test results to depths of 11,000 feet achieved with under 100 watts by Sandia Laboratories, using Develco, Inc. equipment at frequencies below 20 Hz, should be carefully evaluated and exploited if such depths become important to the Bureau. However, it should be kept in mind that such a downlink transmission test has the advantages of power and large antenna size on the surface, and a relatively noise free underground receiver, which is the converse of the mine uplink problem.

c. Equipment

An experimental prototype uplink data monitoring system has been built by WGL for the Bureau. It operates at designated frequencies between 3-5 kHz, utilizes PCM/FSK modulation, a loop transmitter antenna, and is presently installed in the Bureau's experimental mine in Bruceton, Pa. Similar experimental equipment that illustrates the feasibility of uplink data transmission, even with limited available power, has also been built by WGL for miner location applications. An example is the keyed CW electromagnetic transmitter for miner location which utilizes a one turn, 360 foot periphery loop and the miner's 4-volt cap lamp battery to generate a magnetic moment of about 2,000 ampere-meters$^2$ at 2 kHz. Detection ranges in excess of 1,000 feet have been obtained at several mine sites using this and similar units, as reported during this Workshop. It should be noted that the approximately 80 foot overburden at the USBM experimental mine is not considered by the Bureau as being typical of that found over operating mines.

A multichannel uplink data system of practical design suited for installation and test in an operating coal mine with up to 1,000 feet of overburden will soon be needed. The basic monitoring requirements of the in-mine station are now being formulated, so that an overall uplink data communication system can then be designed and optimized for the operating conditions of this mine.

2. The Channel-Transmission Loss

a. Loops

Uplink communications to date have primarily utilized loop source antennas of vertically oriented magnetic moment. These have consisted typically of one turn loops (up to 500 foot periphery) wrapped around one or two coal pillars; and less frequently a smaller one turn loop (up to 100 foot periphery) placed in an entry. Such loops have been preferred over long wire antennas for in-mine installations because of their lower input resistance, fixed impedance characteristics over time, and convenience of installation and maintenance in the adverse mine environment. The primarily vertical magnetic fields produced by vertical axis loops can also offer a signal to noise advantage on the surface in some cases, depending on the sources of the noise, i.e. natural or man-made.

The theoretical results of Wait and ITS, regarding the field strengths expected on the surface from infinitesimal loops of moment NIA placed in homogenous and layered conducting overburdens, are well established and have been found to be in good agreement with experimental data obtained by WGL and Colorado School of Mines (CSM) at several mine sites. For the large overburden depths of interest and sizes of corresponding loops required, the simplifying infinitesimal loop assumptions apply. Furthermore it has been shown by Wait and ITS that typical conducting obstacles, such as pipes, and inhomogeneities found in the transmission path to the surface should produce only small effects on the resultant magnetic field seen at the surface for the under 5 kHz band of interest. WGL and ITS have also shown that the effects of surface topography on the resultant surface field are also small. Consequently these effects can largely be ignored for communications applications, as opposed to location applications where some of the effects can take on greater importance in some cases.

Therefore it was concluded that no new theoretical derivations were required on uplink transmission loss for loop transmitters; but that appropriate curves, tables, nomographs, etc., based on the available theoretical results should be prepared, as an aid to uplink systems designers who desire to apply the theory to typical mine overburdens. Included in these design aids should be curves that show the additional amount of signal loss suffered as the horizontal displacement between surface and in-mine loops is increased. This will help determine the surface coverage obtainable from a single in-mine loop.

b. Parasitic Structures

All of the above results apply for cases in which no large closed loops of wire, cable, or steel roof mesh are close enough to the finite, relatively large, in-mine transmitter loops to allow significant currents to be induced in these parasitic structures, which in turn might reduce the effective strength or field of the transmit loops. The likelihood of encountering parasitic structures on working sections is high, but the degree to which they could adversely affect system performance, has not been ascertained. Since this may be a potential problem to both the uplink data system and the call alert page system to be discussed below, the practical influence of such structures needs to be assessed. However, until that is done, uplink or call alert system transmit loops should be installed away from such structures as steel roof mesh, trolley lines, and probably power cables, since the effects of their presence will decrease with increasing separation.

c. Grounded Wires

Lastly, should there be a renewed interest in comparing the performance of a loop source uplink system with that for a grounded finite straight wire source that utilizes a wire terminated by a roof bolt ground rod at each end, ITS has derived expressions and curves for the magnetic field produced on the surface by such a buried finite wire source. The results apply to the case of the wire inclined at an arbitrary tilt angle to the horizontal in a homogeneous overburden. They show that small tilt angles made by the wire with a flat or hilly surface do not influence the magnitude of the surface field.

### 3. The Channel-Noise

#### a. Past Data

Up until this year very little good noise data pertinent to coal mine environments, underground or on the surface, were available for making comprehensive systems analyses or optimizing uplink or downlink system designs. With respect to noise levels on the surface, the ELF noise measurements made by Lincoln Laboratory for the Navy were the most useful below 300 Hz, even though not taken over coal mines, but in Florida and other parts of the world. Between 300 Hz and 5 kHz the surface noise data were even more sparse, consisting of limited atmospheric noise measurements taken by WGL in Colorado, and limited noise measurements conducted by NBS and WGL at a few coal mines.

These surface data were not considered adequate, because it was suspected that the predominant sources of both broadband and discrete frequency noise on the surface over coal mines would be man-made, since mines were such large power consumers and/or located near industrialized areas. Though broadband atmospheric noise would probably play an important role, broadband noise levels produced on the surface by the mine equipment, and by poorly maintained rural high voltage power lines, were viewed as having a potentially greater influence at a local mine site, except in the case of local thunderstorms. More importantly, even less data were available on the in-mine noise environment for the design of downlink and in-mine systems.

#### b. NBS Mine Noise Measurements

Therefore, during this past year, NBS conducted a major noise measurement effort for the Bureau of Mines in an attempt to characterize in a practical manner the electromagnetic noise environment in and above several "representative" coal mines. Data has been taken at a 600 volt all DC coal mine; a coal mine with 300 VDC rail haulage and shuttle cars, and AC face machinery and belt haulage; a 300 volt DC longwall mine with AC haulage; and a hardrock AC mine with diesel haulage. The measurments encompass operating and quiet conditions for different machines, locations, power centers and boreholes, in working sections, haulageways and on the surface. Some of these noise data have already been processed and made available, with the remainder to become available within the next six months.

In-mine measurements have included wideband recordings from 100 Hz to 300 kHz of three magnetic field components, and of voltages on telephone lines, trolley lines, and roof bolts; from which noise power spectra are being generated. In addition, narrowband (2 kHz) spot frequency recordings were made at eight frequencies covering the 10 kHz to 32 MHz band, of three magnetic field components; from which noise amplitude probability distributions (APD's) are being generated. On the surface, only the components of magnetic field are required, but over a more restricted frequency range, because of the lower frequencies required for uplink systems. The surface wideband recordings for generating spectra cover 100 Hz to 10 kHz, while the narrowband spot frequency recordings for generating APD's cover four frequencies in the 10 kHz to 150 kHz band.

The preliminary results now available from these NBS noise measurements indicate that high levels of discrete frequency noise at harmonics of 60 Hz and 360 Hz predominate over broadband spectrum levels below about 10 kHz, both in the mine and on the surface, with the broadband noise predominating above about 15 kHz, and the levels of both noise types decreasing with increasing frequency. Furthermore, the discrete frequency surface noise levels are highly correlated with in-mine levels below about 7 kHz, the degree of correlation falling off rapidly above 7 kHz. Noise levels also have a strong dependence on distance from power cables, and can vary over dynamic ranges in excess of 60 dB.

c. Whistler and Geomagnetic Data

A representative from Develco, Inc. stated that "mountains" of atmospheric noise data had been taken some years ago in the 1-30 kHz frequency band by Stanford Research Institute with regard to its whistler work. Though some of this data might possibly be useful for the under 5 kHz band of interest, he was also of the opinion that the data had not been analyzed in a form convenient to the uplink application, and that in any case, access to and subsequent understanding of this old data might involve much more difficulty than any potential benefits would justify.

A representative from University of Alberta claimed the presence of a minimum in the geomagnetic noise spectrum between 0.2-8 Hz, with 5 Hz perhaps being the most favorable frequency. Though there was some uncertainty regarding the level of this noise minimum among the Workshop participants, this claim should be checked out, since it might be worth considering for very deep mines. A book by Campbell and Matsushita was given as a reference.

d. Data Utilization

It was concluded that the NBS noise data taken to date at six coal mines and one hard rock mine, together with the planned NBS measurements at an all AC coal mine and another hard rock mine, when added to past atmospheric noise data taken below 10 kHz, should provide a substantial data base from which the design and optimization of mine communications systems can proceed in an orderly manner. Therefore, it was concluded that no new noise measurements over and above that already planned by NBS were required at this time.

In the under 5 kHz frequency band presently of interest to uplink data systems noise, power spectra and dubs of selected NBS tape recordings of the surface noise will be made available to system designers. Surface data up to 10 kHz will also be available if needed. The uplink system designers will need data on the levels of both discrete frequency and broadband noise components: broadband spectrum levels (and amplitude statistics if possible) for optimizing the coding, modulation, and receiver processing for narrowband data uplink; and discrete component levels for estimating likely levels of out-of-band interference, and ways to combat them by choice of operating frequencies and/or receiver signal processing techniques.

To better estimate these noise levels, particularly the broadband noise levels between discrete harmonic components, it was recommended that NBS provide expanded frequency scale spectra, covering only the 0-5 kHz band per spectrum plot, as opposed to the more compressed plots presently being prepared. Spectra for vertical and horizontal magnetic field components on the surface under both operational and "quieter" emergency conditions will be required. Note: these 0-5 kHz expanded spectra will be required not only for the surface noise data, but also for the underground data for use in the design of call-alert and baseband-voice-downlink communications for mine sections. Though not discussed in the working group, amplitude statistics for the broadband levels between harmonics may also be required.

For deep mine applications that may require operating frequencies in the vicinity of 100 Hz and below, the present NBS mine noise data down to 100 Hz and the LL atmospheric noise data down to about 3 Hz may be adequate for designing such systems. The need for additional noise measurements at these low frequencies should be carefully evaluated and justified before embarking on such a measurement program, because of the increased measurement difficulties encountered at these frequencies.

4. <u>The Source</u> - Message, Coding, Modulation, Operating Frequency.

The group agreed that firm conclusions regarding preferred techniques for coding, modulation, and operating frequency for a data uplink were premature, and could only be reached after a detailed overall systems analysis. Such an analysis would need to consider such things as the actual data message requirements, the bandwidth and power available, the transmission loss, characteristics of the noise, etc. Though the frequency band between 1-5 kHz is currently favored, based on past noise data, even this should be re-evaluated in the light of the new and more comprehensive NBS mine noise data.

The present WGL transmitters used for miner location utilize a CW signal that is simply keyed on and off with a ten to one duty cycle, to keep it simple, conserve cap lamp battery life, and to help distinguish it from adjacent power line harmonics. Operating frequencies are located between the harmonics of 60 Hz in the 1-3 kHz band. The present WGL uplink data system installed in the Bureau's experimental mine utilizes PCM/FSK to transmit the monitored data, and operates at select channel frequencies in the 3400 to 4500 Hz band, also placed between 60 Hz harmonics. The location transmitter is described in a Workshop paper, whereas the present experimental uplink data system is described in WGL reports. The specific results obtained with these systems should be reviewed as an aid to future designs.

As mentioned earlier, the data requirements and subsequent systems design have not yet been formulated for the uplink data system that will soon be developed for installation in an operating mine. This system design should benefit from the additional noise data and field experience now available.

5. <u>The Receiver</u> - Sensor, Demodulation/Decoding, Special Processing

As for the source, firm overall conclusions could not be reached, but several suggestions were made. An electrostatically shielded and balanced air core loop was recommended as a sensor. Notch filters were suggested to reduce interference from strong harmonics adjacent to the channel frequency.

The present WGL location receiver utilizes several stages of bandpass filtering to obtain a resultant bandwidth of 6 Hz. Notches as described above apparantly have not yet been required at the mine sites visited to date. The present WGL uplink data system utilizes a phase-locked-loop FSK detector prior to decoding. Neither system was discussed.

Lastly, MIT Lincoln Laboratory (LL) has done extensive signal design and non-linear receiver processing work aimed at optimizing ELF secure narrowband data communications (for the Navy Sanguine program) in the face of highly impulsive ELF atmospheric noise, and occasional discrete power line components. Reductions in required signal power of 10-20 dB have been reported, depending on the level of man-made discrete frequency interference, which apparently makes the techniques less effective. LL has been cooperative in the past by making its noise data and instrumentation information available to the Bureau and its contractors; and by recently offering suggestions regarding computer simulation of receiver design configurations for testing performance in the presence of environmental noise. This work should be reviewed to see if it can be applied to the mine problem in a practical and economic manner, particularly in those cases where transmitter power is at a premium and the noise environment severe. This work has recently been reported in the open literature, and more extensively in LL Technical Reports which are available from LL.

Downlink Voice System

1. Overview

a. Experience to Date

The objective of a downlink emergency voice system is to provide coverage of as large an area as possible to mobile miners during an emergency, in mines with nominal overburden characteristics of conductivity $\sigma = 10^{-2}$ mho/m and depths to 1,000 feet; and to do this with as few antennas on the surface as possible within practical limits. This being the case, the overburden transmission loss, the "quiet-mine" noise data available to date, and the greater space and power available on the surface, have favored direct transmission of 500-3,000 Hz baseband voice signals by means of grounded long wire antennas on the surface. Under relatively "quiet" emergency conditions, the present system designed by WGL with a transmitter capacity of 200 watts, has successfully transmitted intelligible voice messages to miners carrying simple manpack receivers to depths of about 1,000 feet. Mine overburdens of low conductivity will of course extend this usable range, while deeper or more conductive overburdens will quickly deteriorate performance or require significantly more power.

The success experienced under emergency conditions led to speculation that such a downlink voice system could have some beneficial operational applications as well, if the surface transmitter power and manpack receiver processing demands did not become excessive. However system performance was discovered to be even more dramatically affected by the in-mine operational noise environment than by the depth and conductivity. Namely, the noise levels severely deteriorated message intelligibility and usable range, demanding greatly increased power to maintain performance. This behavior is predicted by system analyses by both ADL and WGL, using early NBS and WGL in-mine noise data, and has been confirmed several times in operating mines by WGL. The deterioration occurs mainly because of the high levels of 60 Hz and 360 Hz harmonics produced by the mine machinery and DC power conversion equipment, and less often by the broadband impulsive noise near arcing trolleys, levels that can vary over a dynamic range in excess of 60 dB depending on location and machinery operating cycles. By applying simple corrective measures such as varying the orientation of the manpack receiver antenna for minimum noise pickup, which can be an operational inconvenience, and by severely attenuating the large 360 Hz harmonic component by filtering in the manpack receiver, WGL was able to obtain some improvement in performance; but not enough to make it a dependable and practical system under mine operational conditions.

b. Future Developments

The above experience under operational conditions, when combined with the problems associated with gaining surface access rights over advancing coal mine sections (for the installation of long wire antennas, perhaps several thousand feet in length, or smaller loops, which have to be moved more often) make it very unlikely that the permanent surface installations required for operational applications will be a practical possibility in the near future. Thus in the near term, downlink voice will remain an emergency condition mobile system; thereby keeping the communication problem closer to the one originally treated by WGL, but with some added features.

The emphasis for future efforts on this system should probably be in the development of a reliable, compact, dual purpose receiver to be carried by a miner, preferably integrated into his helmet and operated from the cap lamp battery, as described by H. Parkinson in his paper. It will function as a downlink baseband voice receiver under emergency conditions, and as a call alert page receiver under operational conditions for key mining personnel, as mentioned in Section II. Though the present surface transmitter is apparently adequate to handle several emergency conditions, it too will probably need to be redesigned and optimized: for truly mobile utilization in the sense of being easily transportable by backpack or helicopter to the desired spots above the mine; for compatibility with the new dual purpose miner carried receivers to be developed; and for the mine emergency noise conditions likely to be prevailing. Since the downlink voice transmitter will have to be transported to and installed at selected locations above the mine after an emergency has occurred, the mine or section of interest will most likely be in a nearly power-down noise condition with only essential,lower-powered,electrical equipment such as pumps, fans, etc. in operation.

c. Deep Mines

The above applies to the nominal coal mine conditions specified. The deep hardrock mine situation is a vastly more difficult one as described in the uplink section, requiring frequencies down to 500 Hz and possibly 100 Hz and below even for narrowband data applications. Therefore, unless practical and economical techniques for dramatically compressing the bandwidth required for intelligible voice transmission become available, downlink voice to deep mines on the order of 10,000 feet will not be practically feasible under any noise conditions.

## 2. The Channel-Transmission Loss

### a. Long Wire Antennas

Downlink communications to date have primarily utilized grounded, horizontal long wire source antennas on the surface, which reportedly give good coverage in the mine to a strip of width about equal to the depth of the mine under the wire, and sometimes wider, depending on the depth and available transmitter power. Antenna lengths have typically ranged from a low of about 1,500 feet up to greater than a mile, WGL field experience indicating that a length greater than about three times the mine depth being adequate to assume infinitely long wire behavior for the transmission loss. In the mine, the wire's magnetic field is primarily horizontal, with a gradually increasing vertical component as one moves away from the wire in a perpendicular direction; as opposed to the field of a surface loop which has primarily a vertical component. In those cases where the position of the miner or communication station is relatively well known and fixed, a large one turn loop, like that for the uplink, placed over the miner's position can offer a performance advantage as well as one of convenience, depending on the orientation of the miner's receive loop and the direction of the maximum noise component in the mine.

Grounding of the long-wire antenna has been accomplished by means of four or more ground rods at each end of the wire, with special care being taken to ensure good connections by the use of mud and copious amounts of rock salt. In this manner, total resistance values between about 50 and 100 ohms can be achieved for the long wire antenna; however, maintaining these values over long periods of time can sometimes be a problem.

To establish values of average overburden conductivity for estimating system operating ranges at different mine sites, the well established dipole-dipole measurement technique has been used extensively, and found to give results that agree reasonably well with system test results in most cases over coal mines.

The theoretical results of Wait and ITS, regarding the magnetic fields expected underground from infinitely long, insulated wire sources, placed on the surface of homogeneous and layered conducting overburdens, are well established and have been found to be generally in good agreement with experimental data obtained by WGL and CSM at several mine sites. Similar results have been obtained for surface loops. However WGL field experiences have also revealed a somewhat greater tendency for occasional experimental deviations, from predicted field strength values for the long wire antennas. A possible cause cited for this behavior was the presence of long conductors such as power cables, trolley wires, or rails in the mine, or large inhomogenieties in the overburden. This bears some further investigation.

A constant current assumption is used throughout these derivations. This has been shown to be valid for the frequencies of interest provided the conductors are insulated, which they are in practical applications of interest. The Navy experience in particular, with the huge Sanguine transmit antenna, provides good testimony to the validity of this constant current assumption.

ITS and Wait have also derived expressions and curves for the underground magnetic and electric fields produced by finite, grounded, insulated wire antennas on the surface of a homogeneous, unlayered half space, and for the converse situation of the surface fields from buried finite grounded wires. These cases are more closely related to actual field installations. Both analyses reveal that a finite grounded wire can be treated as an infinitesimal dipole when the observation distance, or depth, is more than about twice the cable length; and treated as an infinitely long wire when the observation distance is less than about one quarter of the cable length, this latter behavior having been experimentally observed at several mines by WGL. In between these depths neither approximation is good, the exact curves or analytical formulation being required. Examination of these curves also indicates only slight departure from infinitely long wire field values for distances up to half the length of the wire, and a reduction from infinite wire field values of only about 3 to 6 dB up to distances, or depths, equal to the length of the wire. The degree to which this behavior changes as the observation point moves toward and beyond the end of the wire was not discussed, but should be obtainable from the analysis. These results will be quite useful for determining minimum practical lengths for surface and underground antenna installations, and as a means for understanding observed experimental behavior.

It was concluded that no new theoretical derivations were needed for loops or infinitely long wire sources on the surface for downlink transmission loss, but as in the uplink case, appropriate practical curves, tables, nomographs,etc. be prepared based on the above results for homogeneous and layered overburdens. Similar curves, nomographs, etc. are needed of the magnetic and electric fields for the finite wire cases treated by ITS. As in the uplink case, curves should be included that depict the increase in signal loss with horizontal in-mine movement away from the long wire, finite wire, and loop positions on the surface, in order to determine in-mine coverage areas.

The effects of a layered overburden on the fields of finite grounded wires have not been treated yet. If it is concluded that layering is likely to influence the downlink field behavior in a significant manner, this case should also be treated by analysis and corresponding practical application curves produced. A summary assessment of the importance of layering to the fields produced by the other sources would also be desirable. Lastly, new and better ways of quickly making good, and long lasting, ground terminations in different ground covers should receive some attention.

b. Parasitic Structures

Long wire and loop antennas deployed on the surface are not as likely as in-mine installations to encounter parasitic structures in their immediate vicinity, unless they have to be deployed in and across the streets of a town, or perhaps directly over a gas pipe or under power lines in rural areas. In the first case the complexity of the parasitic structure configuration will probably defy analytical treatment, and what is perhaps more needed is a practical strategy for choice of antenna type and its deployment, based on present knowledge. In the second instance, Wait and ITS have examined cases of long wire sources parallel to buried conducting non-insulated cylinders.

These results should be examined for their potential application to the gas pipe structure. However, since the effects of such structures generally decrease with increasing distance and orientation angle, perhaps a practical solution to this potential problem is again a deployment strategy for minimum effect, when the presence of this conductor is known and flexibility in antenna deployment is available.

In the section and haulage ways at the receiving end of the downlink, metal structures in the vicinity of the man-carried receiving antennas may play a more important role in altering or providing a shielding effect to underground fields, and, may account for some of the lower than predicted levels experienced by WGL in a few instances. Prime suspects for these infrequently reported anomalies could be closed loops made by two or more vehicle trolley poles across the trolley-track transmission line, say in the vicinity of the section loading point, or steel mesh used for roof support in the entries of some mines. The effects of these structures should be estimated using approximate methods, to see if they, as opposed to large unknown conducting anomalies in the overburden, could account for the significantly reduced horizontal field strength levels observed.

### 3. The Channel-Noise

As concluded during the workshop and discussed in the downlink overview section, it can be assumed for the purpose of system design and optimization that the mine or mine sections will be in a non-operational, power-down, condition during the operation of the downlink emergency voice system. All major mining and haulage equipment will be turned off, only minor equipment such as pumps, fans, etc., may be left on.

The in-mine wideband noise recordings made by NBS should provide a more than adequate data base from which to optimize the design of the downlink baseband voice system. Expanded frequency-scale power spectra covering the 0-5 kHz band, and depicting discrete frequency and broadband noise levels of both horizontal and vertical components of the magnetic field intensity will be needed. Dubs of selected noise tape recordings are also desired for testing receiver processing techniques and overall system performance in the laboratory. Of particular interest will be data during quiet times and locations on the sections and haulageways, that characterize the emergency power down conditions. Consultation with Bureau of Mines and NBS staff will no doubt be helpful if not necessary in the selection of measurement conditions and data that typify this condition.

### 4. The Source-Message, Coding, Modulation, Operating Frequency

The source topic was given only brief treatment by the group. It was noted that performance calculations by ADL using early NBS and WGL mine noise data indicate that intelligible downlink baseband voice reception is possible to 1,000 feet in $10^{-2}$ mho/m overburdens, with under 50 watts of average power under low noise mine conditions. This kind of performance is supported by WGL experience in the field. Indeed, even as little as 5 watts may be required under some highly favorable non-operational conditions. (These reasonable average power requirements can climb to prohibitive levels above 10 kilowatts under operational conditions in DC mines.)

The emphasis for the downlink voice system has remained on the direct transmission of baseband voice signals through-the-earth, particularly under the relatively favorable emergency power-down noise condition. Under this condition, the high-level harmonics of 60 Hz, and particularly those of 360 Hz, will be greatly reduced. Updated performance and overall systems analysis calculations based on the more comprehensive mine noise data recently taken by NBS will help to verify (or deny) the desirability of this frequency band of operation, and better establish the required power levels. These noise data should also help identify transmitter signal conditioning techniques and receiver signal and/or noise processing techniques that can be used to reduce the power, size, and weight required for the mobile, emergency surface transmitter.

The use of pre-emphasized and/or clipped speech upon transmission were suggested for consideration as ways to reduce the peak power requirements of the transmitter, while sacrificing only little intelligibility for the same average speech power transmitted. Means of significantly reducing the bandwidth needed (by more than an order of magnitude) to transmit voice intelligibly have been claimed in the literature. Since such reductions would correspondingly reduce transmitter power, these reported methods should also be investigated.

An alternative method for improving mine communications was also recommended by the group as perhaps a long-term goal for the mining equipment suppliers. Namely, the effective suppression of electrical noise at its source in the equipment whenever practically possible, by means of improved designs and/or addition of special noise suppression equipment.

5. <u>The Receiver-Sensor, Demodulation/Decoding, Special Processing</u>

a. <u>Downlink</u>

As for the source, only brief consideration was given to this topic. A helmet mounted loop antenna design is desired, together with a similarly mounted compact dual-purpose receiver, as mentioned in the system description section. The call-alert function of the receiver will be discussed later.

Use of notch filtering to reduce the interfering effects of high-level harmonics of 60 Hz and 360 Hz, thereby reducing required transmitter power, was the principal suggestion. Such filters have been successfully applied in France, and reference material on these applications will be forwarded to the Bureau of Mines by representatives of the University of Lille. Dramatic improvements in voice reception in the face of harmonic interference have also been demonstrated by ADL in the laboratory, with a breadboard design of a simple electronic commutator-type filter that is particularly suited to rejecting harmonic signals. The French and ADL reported results should be reviewed, together with other reported notch filter work. They should be reviewed for their effectiveness against the mine emergency condition harmonic interference; and for their practical application to a compact helmet mounted receiver, should the measured harmonic levels warrant the use of notch filtering under emergency power-down conditions. In regard to this latter point, it may be necessary to evaluate the effect of pure or complex "tones" of noise, such as those created by harmonics of 60 Hz and 360 Hz, on the intelligibility of received speech. The effect of direct audio noise in the mine environment (which will probably be low under emergency conditions) should also receive brief consideration along with that of the overall speech sound level to be delivered to the miner.

b. Uplink

Performance calculations, similar to those for the downlink discussed above have also been performed by ADL for a baseband voice uplink using a multiturn 100-foot periphery loop transmit antenna instead of a long wire. The results indicate that, except under the most favorable conditions of depth (300 feet) and the quietest of surface noise conditions, the levels of transmitter power, voltage, and current required are well in excess of those demanded by intrinsic safety, long operating life, and practical size and weight for an in-mine emergency unit. These uplink transmitter requirements for voice should be reconfirmed, along with those for the downlink voice system, in light of the more comprehensive NBS mine noise data now available and the larger in-mine loop antennas being considered. However, it appears that an uplink voice system that can operate from available emergency power will continue to remain impractical until an economic and practical way is found to significantly reduce the bandwidth required to transmit intelligible speech.

Sidelink Call Alert Coded Page System

1. Overview

The call alert system is a recent by-product of the success experienced with the experimental electromagnetic CW transmitter developed by WGL for locating miners trapped beneath overburdens of $10^{-2}$ mho/m conductivity to depths of 1,000 feet. As mentioned previously, the location transmitter is intrinsically safe, operates from a miner's 4-volt cap lamp battery into a one-turn loop placed in an entry or wrapped around a coal pillar, and generates a periodically interrupted CW signal in the 1-3 kHz band. This signal is detectable on the surface above the miner and is suitable for locating the miner's horizontal position. The development of this location transmitter has now progressed to where an improved preproduction prototype unit is being manufactured by Collins Radio Co. in limited quantities for testing in some operating mines.

Since the horizontal ranges desired for the call alert system described in section II are commensurate with the vertical ranges obtained for miner location, the Bureau is presently giving high priority to the development of a call alert page system centered around an adapted version of the WGL location transmitter. As presently conceived, this paging transmitter will be activated by means of a carrier signal sent over the mine phone line from the surface to the desired section. The call alert transmitter will be connected to a loop wrapped around a coal pillar, perhaps at the section loading point, and will transmit a single frequency tone (perhaps simply coded) to a compact, dual-purpose, helmet-mounted receiver worn by the individual being paged to the section's mine phone. Under low noise emergency conditions, this receiver will be operable in a baseband voice mode for downlink message reception. Under high noise operational conditions, it will operate in a narrowband call alert mode, receiving a prearranged CW paging signal spaced between the strong 60 Hz harmonics usually present under these conditions.

A first generation experimental call alert system has been built from existing hardware by WGL, and installed in the Bureau's experimental mine to demonstrate concept feasibility in a non-operational environment. Though the operating frequencies of the present experimental unit are in the 1-3 kHz band, to take advantage of the frequencies available with the present location transmitter, an overall system analysis for an operational noise environment may reveal a more effective operating frequency.

Overall system requirements are presently being formulated by the Bureau. These will form the basis for subsequent systems analysis and optimization of designs that can be converted into practical, intrinsically-safe hardware for day-to-day use in operating mines.

2. <u>The Channel-Transmission Loss</u>

a. <u>Loops</u>

In-mine call alert paging is a sidelink application utilizing two essentially coplanar loops, while miner location is an uplink application utilizing two essentially coaxial loops. Examination of Wait's theoretical coupling curves for infinitesimal loops buried in homogeneous overburdens reveals that the operating range for a horizontal coplanar geometry is reduced by only about 20% over the range for a vertical coaxial geometry, for ranges in the vicinity of three skin depths. This operating range is reduced even less at greater distances. Vertical ranges in excess of 1,000 feet have been obtained with the location transmitter. At 2 kHz (the center of the 1-3 kHz operating band of the location transmitter), the three skin depth range is 1,100 feet, which gives rise to a potential sidelink operating range of 900 feet. This 900 foot range is in excess of the 400 to 800 foot range needed for call alert coverage of the typical 600 by 600 foot section mentioned in section II. The above range conclusions are, of course, based on equal noise conditions for each case. Since the noise environment will likely be more severe for the in-mine, operational, call alert application, its effect on operating range and transmitter/receiver design has to be determined.

At the under 5 kHz frequencies of present interest for the call alert system, the theoretical work of Wait/ITS has shown that the effects of layering (such as that found above and below coal seams) and air-filled cavities (such as tunnels in coal seams) should not be significant for loops, and therefore can largely be ignored for communications applications. Similarly, the infinitesimal loop theoretical results should be adequate for making performance predictions, particularly at the desired range limits, for mine sections <u>free of parasitic influences</u>. At ranges close to the loop installation, the infinitesimal loop results will tend to overestimate signal strengths somewhat. This discrepancy will become important primarily when treating potential coupling to nearby parasitic structures, as discussed below. Therefore, curves, tables, nomographs should be prepared for the vertical magnetic field component in the plane of the transmit loop, based on the available theoretical results for coplanar infinitesimal loops. These can be used temporarily for making preliminary performance predictions until more information is forthcoming on the effects of the conductors prevalent in mine sections.

b. Parasitic Structures

Mine sections typically contain many conductors, such as trolley wires and rails, fixed and trailing power cables, roof bolts, and sometimes steel roof-supported mesh, that can affect the strength and orientation of magnetic fields. Therefore, a series of limited signal strength measurements should be conducted in operational mine sections, and in other mine locations that are relatively conductor-free. These simple experiments are needed; to verify whether the homogeneous-overburden coplanar loop results can be applied with confidence to operational sections, and to formulate practical design guides for operational sections. Preliminary results from field measurements taken by ADL in the Bureau's experimental mine indicate that significant departures from the theoretical results can in fact occur.

In parallel with the above field measurements, corresponding theoretical analyses are needed to predict the degree to which the direction and strength of the magnetic fields produced in the tunnels, by finite loops wrapped around coal pillars, will be affected by the above mentioned conductors in working sections of the mines. Of particular interest will be the effects caused by trailing and fixed power cables, roof bolts, and trolley wire/rail structures, which appear manageable analytically. The potential problems caused by heavy metal mesh occasionally used for roof support were acknowledged, but assigned a lower priority for analytical treatment, because of the infrequent use of this mesh and perceived analytical difficulties.

ITS has done some investigation of the currents induced in a thin, infinitely long, cylindrical conductor by a nearby infinitesimal loop transmitter. This work reportedly is easily extendable; to include the effects of the magnetic field produced by this induced current, and to include the effects produced by a finite loop source. The utility of this approach should be investigated, and pursued if found applicable.

ITS has also examined the influence of buried spherical and prolate spheroidal conducting objects on the fields produced by infinitesimal loop sources. Though originally done in connection with the miner location problem, the results can be applied to the call alert application, to estimate the likely field effects produced by machinery and shuttle cars. For the frequencies, sizes, geometries, and distances of interest, these objects will not significantly alter the magnitude of the fields, but mainly their direction somewhat in the immediate vicinity of the objects. No further investigations of this area were recommended.

c. Roof Bolts

If a finite wire terminated by roof bolts is shown to be a favorable transmit antenna for the roof bolt paging system, a suggestion was made that it also be considered for use in the call alert system.

3. <u>The Channel-Noise</u>

Since this is a narrowband operational system for mine sections, the in-mine wideband noise recordings made by NBS should provide an adequate data base. Of particular interest will be expanded frequency-scale power spectra showing levels of discrete and broadband noise covering the 0-5 kHz band; and representing data taken primarily on working sections in the vicinity of face machinery and power cables and conversion equipment, under representative operating conditions. Vertical field components of the noise will be mose important for this application. Dubs of select recordings will also be desirable as mentioned previously. Although frequencies below 5 kHz are presently favored, data can and should be examined above 5 kHz for this system.

4,5. <u>The Source and Receiver</u>

Only little attention was devoted to this topic, with the group agreeing that a definition of system requirements and an overall system analysis were needed to identify the most favorable and practical system design approaches. However, a few brief comments were made.

The transmitted call alert signal could be a single tone, keyed on and off with a fixed duty cycle, as in the present experimental unit. For a single page signal per section, the simple, single tone system now used in the experimental unit could be adequate. For several pages addressable to different individuals per section, some means of coding the single tone, or use of multiple tones would be needed. The most favorable coding method from practical and noise immunity standpoints needs to be determined.

On the receiving end, it was noted that notch filters may be needed to minimize interference from 60 Hz harmonics adjacent to the signal frequency. The most practical and effective noise processing techniques suited to a compact, helmet-mounted receiver need to be determined.

As mentioned in section II, this system could conceivably share equipment with an uplink data station also located on the mine section.

<u>Sidelink Roof Bolt Voice Page System</u>

1. <u>Overview</u>

The roof bolt voice paging system is a system conceived and recently developed by the Bureau for transmitting voice messages to key individuals carrying small pocket pagers on working sections under operational conditions. A prototype, using readily available commercial equipment, is presently installed in the Bureau's experimental mine to demonstrate its feasibility in a non-operational environment. The system concept developed as a result of some successful in-mine experiments performed by the Pittsburgh Mining and Safety Research Center; whereby a 20-watt trolley phone 88 kHz FM transmitter was connected to two roof bolts approximately 50 to 100 feet apart in an operating mine, and its voice transmission then received at distances up to about 600 feet away with a small pocket pager utilizing a ferrite loop stick antenna.

Limited field experience to date indicates that operating ranges commensurate with the 400 to 600 feet required to provide section coverage may be achievable, under operational conditions, with an operating frequency in the vicinity of 100 kHz. At this point in time a more quantitative understanding of the transmission loss and what affects it is needed; in order to determine the most favorable operating frequency, to develop practical guidelines for tailoring installations and estimating performance in different mines, and to eventually develop an improved system.

2. The Channel-Transmission Loss

a. Finite Wire Antennas Terminated by Roof Bolts

The finite wire antenna in this case is an insulated wire that runs along the roof of a tunnel and is terminated at each end by attachment to a roof bolt. Field experience to date has found the total termination impedance for such roof bolt pairs, separated by 50 to 200 feet, to fall in the range of 120 to 50 ohms resistive. Theoretical curves and supporting experimental data are needed, to adequately describe the behavior of the magnetic fields produced in the tunnels throughout a section in which such a finite wire transmitter is located.

The theoretical work of Wait and ITS on finite wire antennas buried in homogeneous overburdens, described in sections IIA2c and IIB2a, should be particularly useful in this regard and for estimating system coverage areas in mine sections. Though the present results are for the electric and magnetic fields produced on the surface from such buried antennas, ITS maintains that the desired field strengths in the coal seam tunnels can be easily obtained from its present buried-finite-wire analysis. This case of interest corresponds to receiver locations below, but in the immediate vicinity of, the plane of the finite wire.

Frequencies presently being investigated for this voice page application range from 10 kHz to 300 kHz, with present experimental systems operating around 100 kHz. Although the frequencies in the upper part of this band are higher than originally anticipated for buried finite wire applications, ITS believes that its present analysis should apply.

Therefore, it was concluded that the ITS theoretical analysis of the fields from buried finite wires should be used to determine the desired magnetic fields in the coal seam, in the 1-300 kHz band; and to prepare appropriate practical curves, tables, etc. for use by system designers. In addition, since the overburden is usually layered above and below coal seams, and since layers of varying conductivity can potentially influence the fields from finite wire antennas more than those from finite loops, a theoretical analysis to determine the effects of a simple, representative, layered model should be performed.

The non-conducting volumes created by the grid of tunnels in the coal seam were considered too difficult for exact analytical treatment at this stage; and in fact may not create significant effects on the magnetic fields in the tunnels, because the tunnels are relatively narrow and the currents can still flow without much alteration through the wider coal pillars.

Collins Radio and Spectra Associates are also reported to have performed theoretical analyses of the fields from buried wires, for the infinitely long and infinitesimally small cases. This work should also be reviewed, compared with the ITS results, and utilized if applicable.

Collins Radio has also conducted some limited measurements of the magnetic fields produced by 52 feet long, finite wire roof bolt antennas in an operating mine. Three field components were measured at three distances between 300 and 700 feet away from the finite wire, in both the broadside and axial directions, and at five frequencies in the 1-50 kHz band. Though these measurements do not fully characterize the expected transmission loss behavior, the data serve as a good starting point for comparisons with theory and establishing practical design guidelines. More measurements are needed, covering a greater range of distance, frequency, and roof bolt spacing, and particularly in mine working sections.

b. Parasitic Structures

As in the case of the call alert system, a roof bolt system installed in a working section can be expected to encounter many conducting parasitic structures that may alter the directions and magnitudes of the signal magnetic fields. These effects may even be magnified for finite wire systems operating at the higher frequencies anticipated. Indeed, some limited field measurements taken at 88 kHz by ADL, for a roof bolt antenna installation in the Bureau's experimental mine, indicate an extremely high variability in the levels of the measured vertical field component at comparable ranges from the roof bolt antenna. Therefore, and for the same reasons given for the call alert system, a similar experimental and theoretical effort is recommended to resolve the issues concerning the effects of parasitic conducting structures found in representative working sections of operating mines.

3. The Channel-Noise

Since the roof bolt system is a voice paging system for use under operational conditions, its operating frequency will most likely be above about 10 kHz, where the operational noise levels decrease to more tolerable levels. Present consideration is being focussed on the 10 kHz to 300 kHz band. The present experimental system operates at 88 and 100 kHz, but since these frequencies are already utilized by mine trolley wire carrier systems, alternative non-interfering frequencies are also desirable.

As for the other systems, the recently obtained NBS in-mine noise data should serve as a more than adequate data base for systems analysis and optimization in the 10 kHz to 300 kHz band. From the wideband tape recordings, power spectra for horizontal and vertical magnetic field components will be available, depicting discrete and broadband noise levels over the frequency range from 0-100 kHz and 0-300 kHz. In addition, noise amplitude probability distributions and rms levels will be available from the narrowband (2 kHz) spot frequency noise recordings, at eight frequencies over the 10 kHz to 32 mHz band, four of which fall below 300 kHz. Appropriate dubs of selected tape recordings for both types of noise measurement should also be available. Detailed reports documenting these measurements and data will soon be published by NBS.

### 4,5. The Source and Receiver

The present experimental system is designed around a commercially available 20 watt, mine trolley wire phone transmitter that employs conventional FM modulation and an industrial pocket pager FM receiver that operate at a carrier frequency of either 88 or 100 kHz. Lack of time prevented discussion of the overall system by the group, but it was concluded that the degree to which this system can or should be optimized or otherwise improved with regard to performance, practicality, intrinsic safety, etc. will eventually be determined by the system requirements and a subsequent system analysis.

# D. SUMMARY REPORT OF OPERATIONAL COMMUNICATIONS WORKING GROUP

THROUGH-THE-EARTH ELECTROMAGNETICS WORKSHOP

Golden, Colorado

August, 1973

GROUP CHAIRMAN

MARTYN F. ROETTER
ARTHUR D. LITTLE, INC.

## OUTLINE

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## SUMMARY

The work of the operational communication systems' group dealt with a range of communication needs and functions within mines, primarily along haulageways, to and within sections up to the working face itself, and in mine shafts. A mixture of communication techniques and hardware is needed to satisfy this variety of communication needs within the differing environments encountered in U.S. mines. Substantial progress, both experimental and theoretical, has been made in recent years towards developing alternative communication systems suitable for use in mines which are based on "guided" waves, including wire-less (waveguide-like propagation in mine tunnels) and wire-based systems (leaky coaxial cables or wires). Major priorities identified for further work needed to confirm (or deny) the applicability, and refine the operational specifications of promising communication systems for mine use include:

### Short-Term Projects

- Cost/performance analyses of promising leaky coaxial cable and UHF radio communication systems which require further data from:

  - Experimental investigation under U.S. mine conditions of the performance of potentially applicable leaky coaxial cable communication systems developed in Europe (France, Belgium, and the U.K).

  - Cost estimates on these coaxial cable communication systems.

  - Measurements of UHF radio propagation in low-coal mines.

  - Investigation of the influence of obstacles (e.g. shuttle cars and section machinery) in the entries on UHF radio propagation in mines.

- Investigation of the problems of transmitter and receiver coupling and termination matching associated with the two-way propagation of low frequency radio waves in hoist shafts.

Longer-Term Projects

i.e. of lesser urgency or where less information is currently available.

- Investigation of techniques for coupling UHF radio to leaky coaxial cable communication systems.

- Delineation of the role of, and needed interfaces for, operational communication capability related to emergency, paging and monitoring functions.

## OPERATIONAL COMMUNICATIONS FUNCTIONS

The communication functions under discussion in this report are primarily:

- Two-way communication along main haulageways up to 4-5 miles long, to vehicles and to maintenance personnel.

- Two-way communication in sections up to working faces; all entries near the working face should be covered, but possibly only a limited proportion of those at or near main haulageways. Communication with roving personnel at up to 3,000 feet away from main haulageways must be established. More than one kind of working face must be dealt with, i.e. room and pillar (predominant in the U.S.) and longwall.

- Two-way communication in mine hoist shafts (on the order of 10,000 feet long).

Two distinctive categories of communication are involved, the first depending upon a base station, and the other dealing with direct mobile-to-mobile communication.

Although not discussed in detail, it is recognized that the communication systems designed to fulfil these purposes may interface with other communication systems such as trolley phone, as well as play a role in assuring some emergency, paging (call alert), and one-way monitoring communication functions.

## ENVIRONMENTAL CONSTRAINTS

The primary constraints recognized as affecting the communication systems under consideration are:

- Daily utility of equipment
- Intrinsic safety
- Ruggedness and resistance to harsh mine environment
- Available power
- Weight and size limitations
- Cost limitations

The electromagnetic noise environment at the frequencies typically proposed or employed (a few MHz up to 1 GHz) appears not to be a significant factor in determining communication system performance. A possible exception to this rule or slightly less clear-cut situation may prevail in the case of low frequency (LF) radio propagation proposed for communication in mine shafts (at frequencies of a few tens of kilohertz).

## OPERATIONAL COMMUNICATIONS SYSTEMS

Several alternative communication systems are in principle technically capable of satisfying the communication needs just described. A tentative conclusion in the light of our present state of knowledge is that communication along haulageways may be efficiently provided by one or more of the proposed leaky coaxial cable systems discussed later. However, leaky coaxial cable systems seem incapable of providing communications capability at more than 10 to 20 meters lateral distance from the cable. Thus in order to provide wide area communications coverage within the network of tunnels in a coal mine section, it would be necessary to string cables along most of them. The cost and practical obstacles to stringing all this cable in a continually changing section geography favor the application of UHF radio for wide area communications within a section. There is both theoretical and experimental evidence to indicate that UHF radio is capable of providing this function.

Coaxial cable, radio, and low frequency TEM radio wave transmission in the shaft are all potential candidates for providing communication in a mine shaft. No single one of these communication techniques has yet been identified as being especially advantageous in this application.

The communication techniques discussed fall under the general description of "guided" waves and comprise:

- Wire-less (UHF frequencies)

- Wire-based

  - Coaxial cable with periodic radiative structures (INIEX/Delogne)
  - Coaxial cable with high surface transfer impedance (braid outer conductor)
  - Coaxial cable with repeaters
  - Wire pairs
  - Single wire (including LF radio propagation in mine hoist shafts)

It is also recognized that power-line carrier communication techniques are potentially attractive for some of the communication applications under consideration; it is worthwhile to investigate power line carrier systems further, however, no serious evaluation of them was made in this workshop. Power line carrier systems are already used along the trolleyway in some mines.

In the following,promising communication systems are identified and their current state of development described. Problems and areas where additional data or further theoretical understanding are needed are listed, and priorities for future development work are suggested.

UHF Radio (U.S.)

1. State-of-the-Art

Marked progress has recently been made in understanding the characteristics and capabilities of UHF radio wave propagation along coal mine tunnels. Measurements taken in mines by Collins Radio indicate that effective communication can be provided throughout most of a typical U.S. coal mine section by UHF radio. A theoretical analysis carried out by Arthur D. Little, Inc. (ADL) staff based upon the hypothesis of waveguide propagation is in agreement with the Collins measurements in several important respects. The theoretical model is believed to reflect the basic structure of UHF radio wave propagation in coal mine tunnels, although it is presently not intended to give accurate signal loss estimates around corners when either the transmitter or receiver is near the corner (less than 50-100 feet). In those cases the model's loss assymtotes will over estimate the loss.

During the workshop an apparent violation of the reciprocity theorem was discovered in an application of the ADL theory to extend Collins Radio's data for a determination of the extent of coverage provided by UHF communication within a section. This apparent violation is believed to result from an application of the ADL model in a region where it is invalid, namely in the corner loss situation just mentioned. The reciprocity theorem must be respected, and a refinement of the model is needed to predict transmission loss around a corner when either the transmitter or receiver is nearby the corner. Collins Radio has re-evaluated the section coverage predicted for UHF radio which can be deduced from their data and extrapolated by the ADL theory, assuming the reciprocity theorem holds. The results of this computation are attached; they are very encouraging.

Leaky coaxial cable communication systems operating between 2-20 MHz appear incapable of providing communication along cross-cuts in which they are not strung, and hence appear both costly and unlikely of implementation for communication in the grid of many tunnels which constitute a section. UHF radio is likely to be more effective in this situation of areal rather than essentially linear or tubular communication coverage. In summary, both theoretical and experimental results obtained to date warrant further development of UHF radio techniques for providing practical communications in coal mine sections.

2. Future Development Programs

(a) Short-Term

No measurements have yet been taken of UHF radio wave propagation in low-coal mines* which constitute a significant fraction of U.S. coal mining activity. These measurements are needed to determine if the different geometry of low-coal as against high-coal mine tunnels permits practical communication of UHF.

Additionally information is needed on the influence of obstacles in entries and tunnels on UHF radio wave propagation. In a coal mine "obstacles" such as section machinery and shuttle cars are inherently present. Some of these obstacles can block the major portion of an entry and may wipe out effective communication to various areas of the mine section as they move around. Multipath propagation effects may help in overcoming this problem; at any rate, data are urgently needed.

Less urgently, it would be revealing to obtain UHF propagation data of higher frequencies (above 1 GHz) where critical tests of the ADL theory, including the selection of the optimum operating frequency, would be possible. In practical terms these measurements are not, as already mentioned, of the highest urgency, as the use of a frequency above 1 GHz for mobile UHF radio is improbable since it would entail significantly more expensive (because non-standard equipment). Standard UHF frequencies for mobile communication are in the 450 MHz band, and the 960 MHz band soon to be opened by the FCC. It may additionally be noted that the FCC may not in any case approve non-standard UHF frequencies for underground mobile communication, even though in principle, use of non-standard frequencies is acceptable for underground use as long as no leakage to the surface occurs. The basis for this attitude may be explained by the ease with which mobile, as against fixed communications gear, may be taken out of the mine for personal use.

*However, the reduced range performance of 420 MHz portable handy talkies recently encountered by Bureau of Standards staff during a noise measurement field trip to a low coal mine appears to partially confirm the significantly higher propagation loss predicted for coal mines by the theory.

The Bureau of Mines should also delineate clearly the alternatives and practical considerations associated with the placing of the UHF transmitter (and possibly repeaters) to provide the best communication coverage within a section, taking account of its continually changing features.

(b) Long-Term

A future scenario may be envisaged in which a leaky coaxial cable communication system is in use along mine haulageways, whereas UHF radio provides communication up to working faces. In this situation the effective exploitation of all the advantages of these two communication techniques would be enhanced by the ability to couple them together. The techniques, costs, and performance of methods practicable to accomplish this coupling should be investigated.

Leaky Coaxial Cable Communication Systems (Europe)

1. State-of-the-Art

Three major classes of coaxial cable communication systems designed for use in mines have been reported as being in various stages of development in Europe.

(a) INIEX/Delogne system (Belgium) employing regularly spaced radiating devices

Much experimental and theoretical investigation of this system has been performed including trials at the Bruceton, Pa. experimental mine of the USBM. The optimum operational frequency is believed to fall in the range of 2-20 MHz. Prototype installations are on order in Belgium, at a price of about $2500/km. Firm production sales prices are not yet available. The INIEX/Delogne scheme appears potentially suitable for application in U.S. mines, although several uncertainties regarding performance/cost trade-offs in typical U.S. mine environments still have to be resolved, as discussed below. These uncertainties are connected in particular with the restraint in U.S. mines, in contrast to Europe, of having to install the cable close to the rib with consequent increases in attenuation, over a more central location in the tunnel, and with the influences on performance of dirt and water on the cable and on the radiative devices.

(b) Coaxial cable with high surface transfer impedance -- specially designed "leaky" braid outer conductor (France)

Theoretical investigations carried out at the University of Lille in France indicate that effective communication along several miles of mine haulageway may be achieved by use of a coaxial cable whose braid outer conductor is designed for "optimum" leakage of radiation. Experimental investigations of this scheme in a French mine are planned to be carried out in a few months' time. The optimum operational frequency is believed to be between 5-10 MHz.

Similar uncertainties exist with regard to the effects of dirt, water, and proximity to the walls of the tunnel on the performance of the proposed French scheme in U.S. mine environments, as were mentioned in the context of the Belgian cable system.

(c) Coaxial Cable with Repeaters (U.K.)

It has been reported that coaxial cable communication systems incorporating repeaters are being tested experimentally in the U.K. At this workshop little information on the cost and performance of this system was available. Additional uncertainties in the performance and cost evaluation of this system are introduced by questions associated with the reliability and maintainability of the repeaters that can realistically be expected in a mine environment.

2. Future Development Programs

(a) Short-Term

Progress achieved in Europe in the development of the coaxial cable communication systems mentioned above should be carefully and continually monitored and evaluated. In particular, cost estimates and further operating performance data should be obtained as soon as possible.

Nevertheless, European results, while valuable and to date encouraging, cannot be directly applied to the different environment of U.S. mines. In particular it appears impossible to install communication cables in U.S. mines in the locations recommended by European researchers. Specifically cables will have to be installed close to the ribs or walls of tunnels. Accordingly different attenuation rates, and correspondingly different optimum operating frequencies or trade-offs between the rate of "leakage" of power and total communication system length may prevail than in the European situation. Experimental investigations in U.S. mines with the proposed European coaxial cable systems are required before their applicability in this country can be definitively confirmed or denied, and if confirmed, operational specifications written (frequency, design of radiative structure or "leaky" outer conductor, and so forth).

(b) Long-Term

As was discussed in the section on UHF radio, techniques for coupling coaxial cable systems to UHF radio communication should be investigated.

## Simple Wire Systems (Europe)

### 1. Wire Pairs

The technical feasibility of communication via waves propagated along wire pairs is well established, and the coupling between and characteristics of the unbalanced and balanced modes of propagation are well understood. However the sensitivity and lack of resistance of simple wire pairs to the deleterious effects of the mine environment (dirt, water, rough handling) tend to rule them out as practical implementations of in-mine communication systems.

### 2. Single Wire

A single wire communication system is impractical as a solution to a mines' operational communication needs along haulageways or in sections, although a similar type of communication system operating in the low frequency (LF) range holds promise for use in mine shafts.

## Low Frequency Radio in a Hoist Shaft (U.S.)

### 1. State-of-the-Art

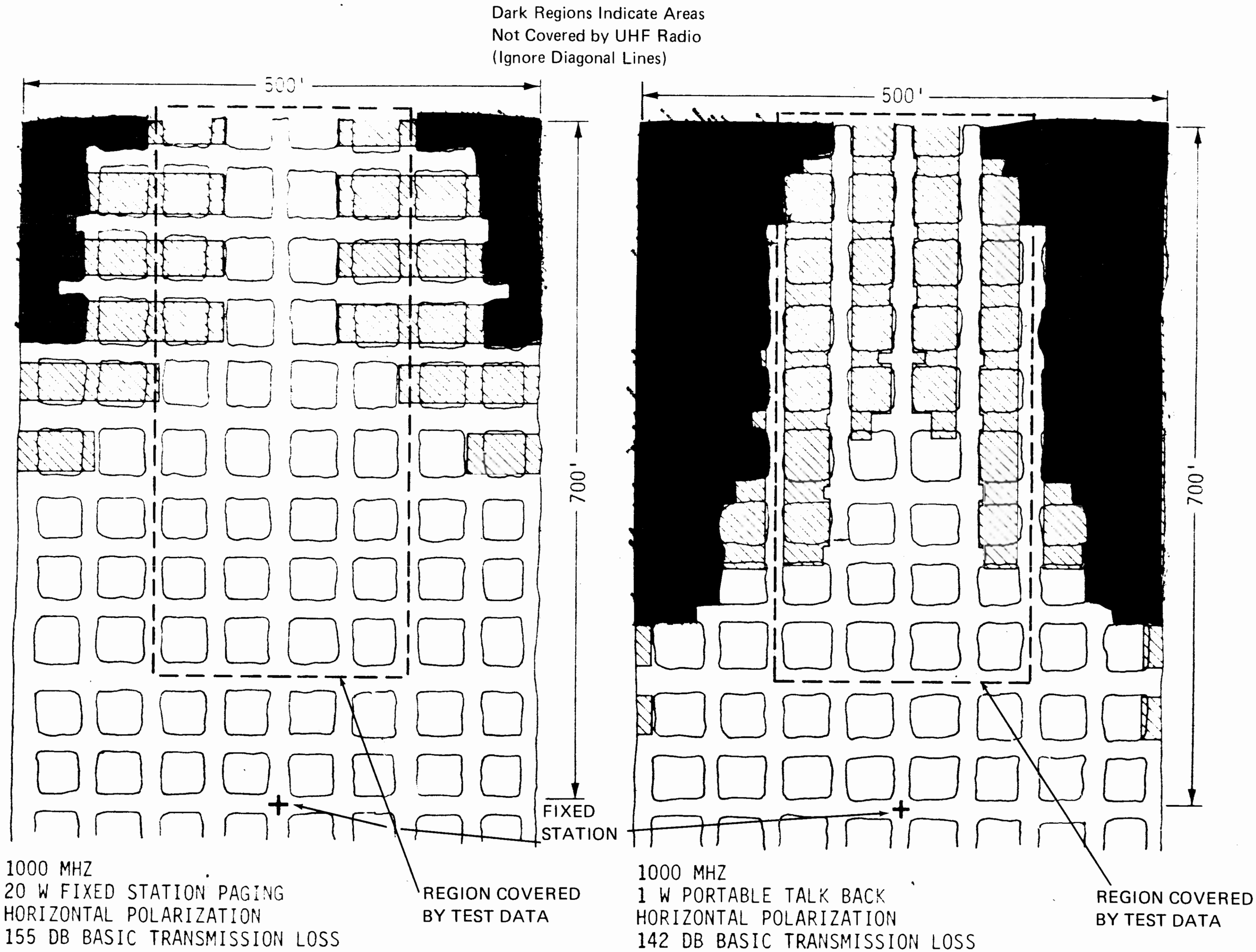
Theoretical investigations at ADL have analyzed the propagation of LF radio waves in deep (10,000 feet) hoist shafts in which the hoist cable is the only metal conductor present. Propagation losses of approximately 2dB over 10,000 feet at frequencies near 50 kHz have been computed. This is a very encouraging result.

### 2. Future Development Programs

#### (a) Short-Term

Two difficulties with respect to LF propagation in hoist shafts have been identified. Firstly, the large penetration of the wave into the rock outer conductor may present a problem with regard to coupling the transmitter or receiver to the transmission line with a minimum of insertion loss. The amount of the insertion loss that can be tolerated has not yet been specified; it may be quite large, in view of the remarkably low transmission losses calculated. The coupling problem merits attention to determine, for example, how closely to the theoretical distribution of the vertical component of current density, in the fundamental propagation mode, should the actual driving current be distributed.

Secondly, in order to minimize reflections, both ends of the hoist cable-shaft transmission system must be terminated in approximately the characteristic impedance of the transmission line. Further work is needed to resolve the question of how, how well, and how expensively matching terminations may be provided.




**Source:** Collins Radio Co.

**FIGURE 1 PREDICTED COVERAGE OF MINE SECTION BY UHF RADIO FOR TWO ASSUMED SITUATIONS**